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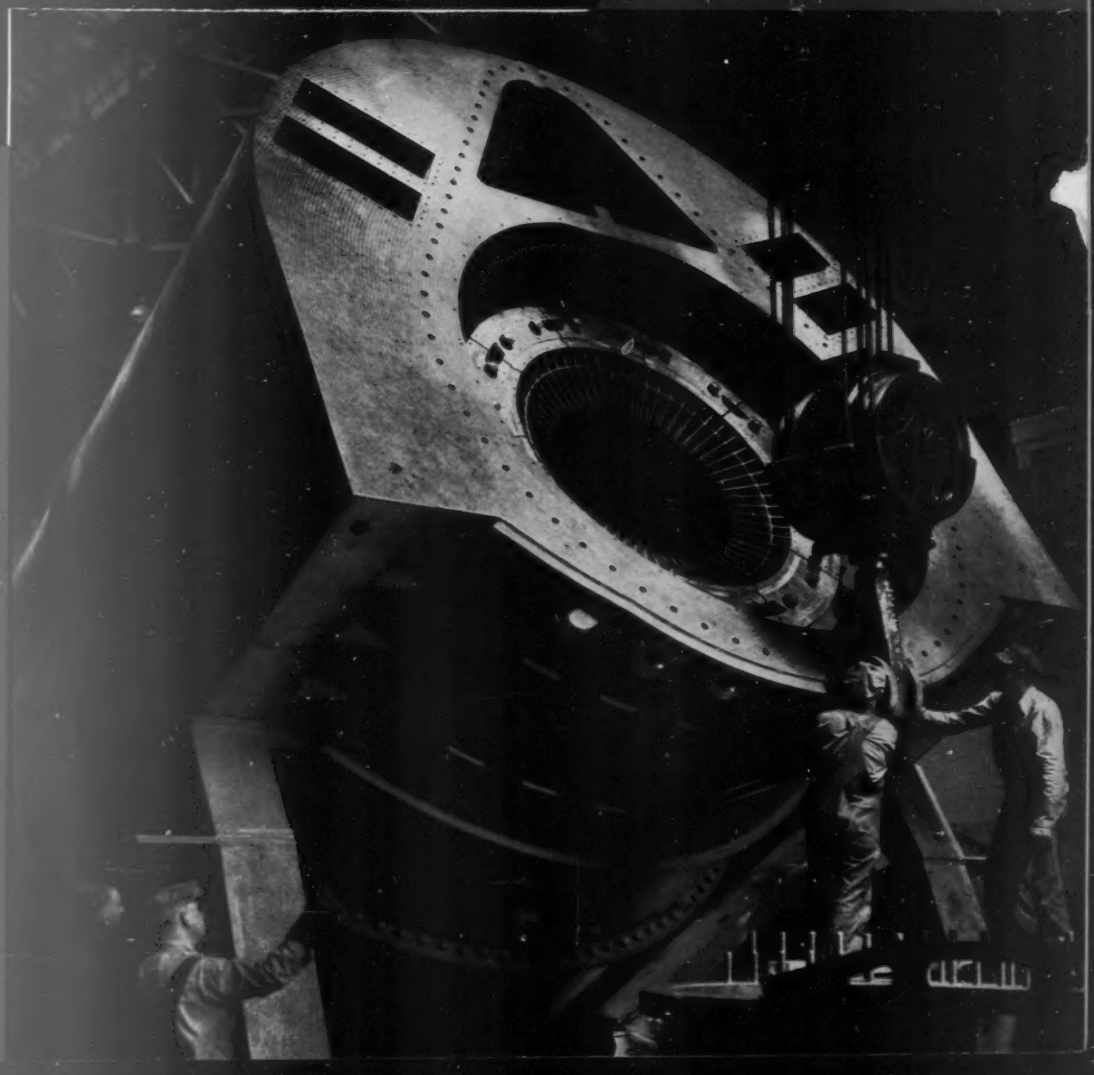
ELECTRICAL REVIEW

June • 1943



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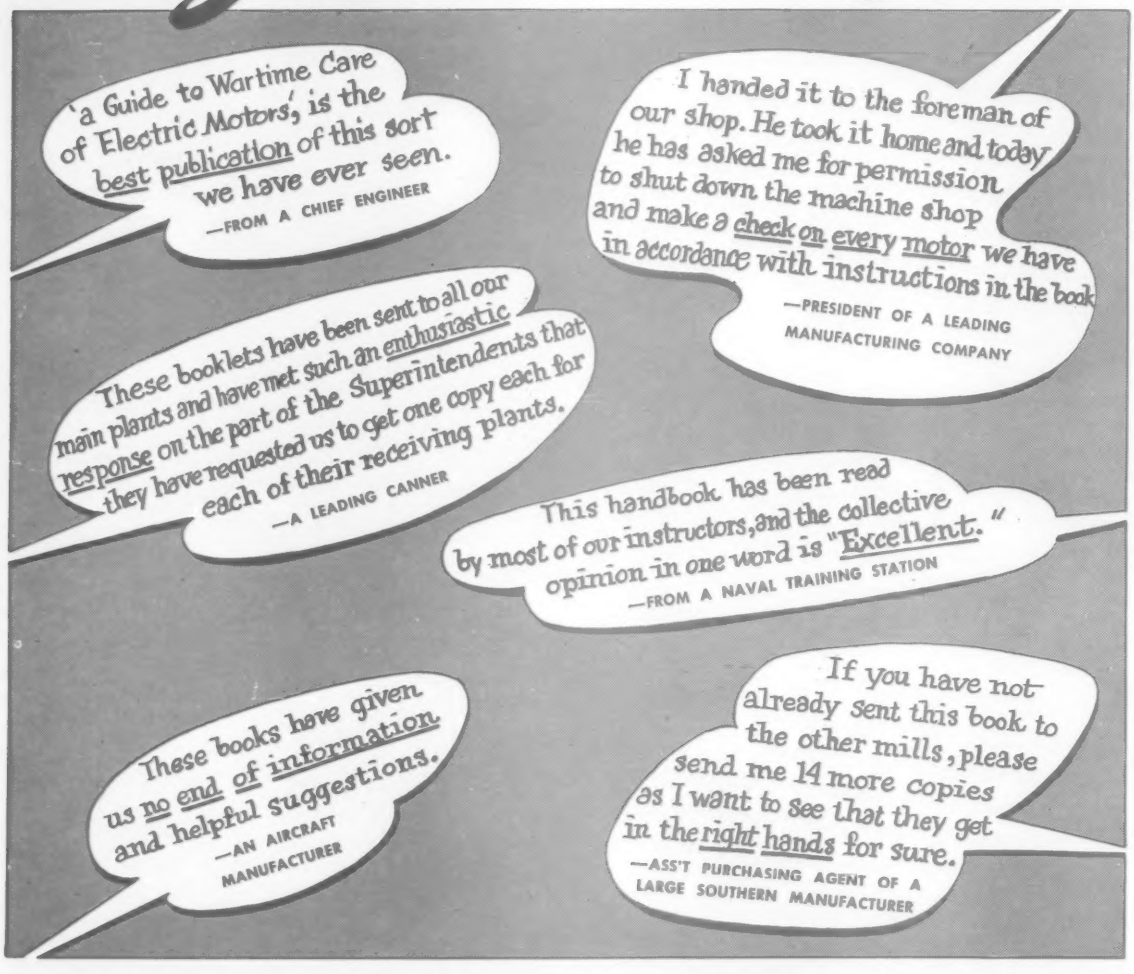
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Vol. VIII . . . No. 2

June, 1943

Allis-Chalmers
Electrical Review

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Issued quarterly. Subscription rates: U. S. Mexico and Canada, $2.00 per year; other countries, $3.00. Address Allis-Chalmers Electrical Review, Milwaukee, Wisconsin.

Printed in U. S. A.
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Allis-Chalmers Mfg. Co.

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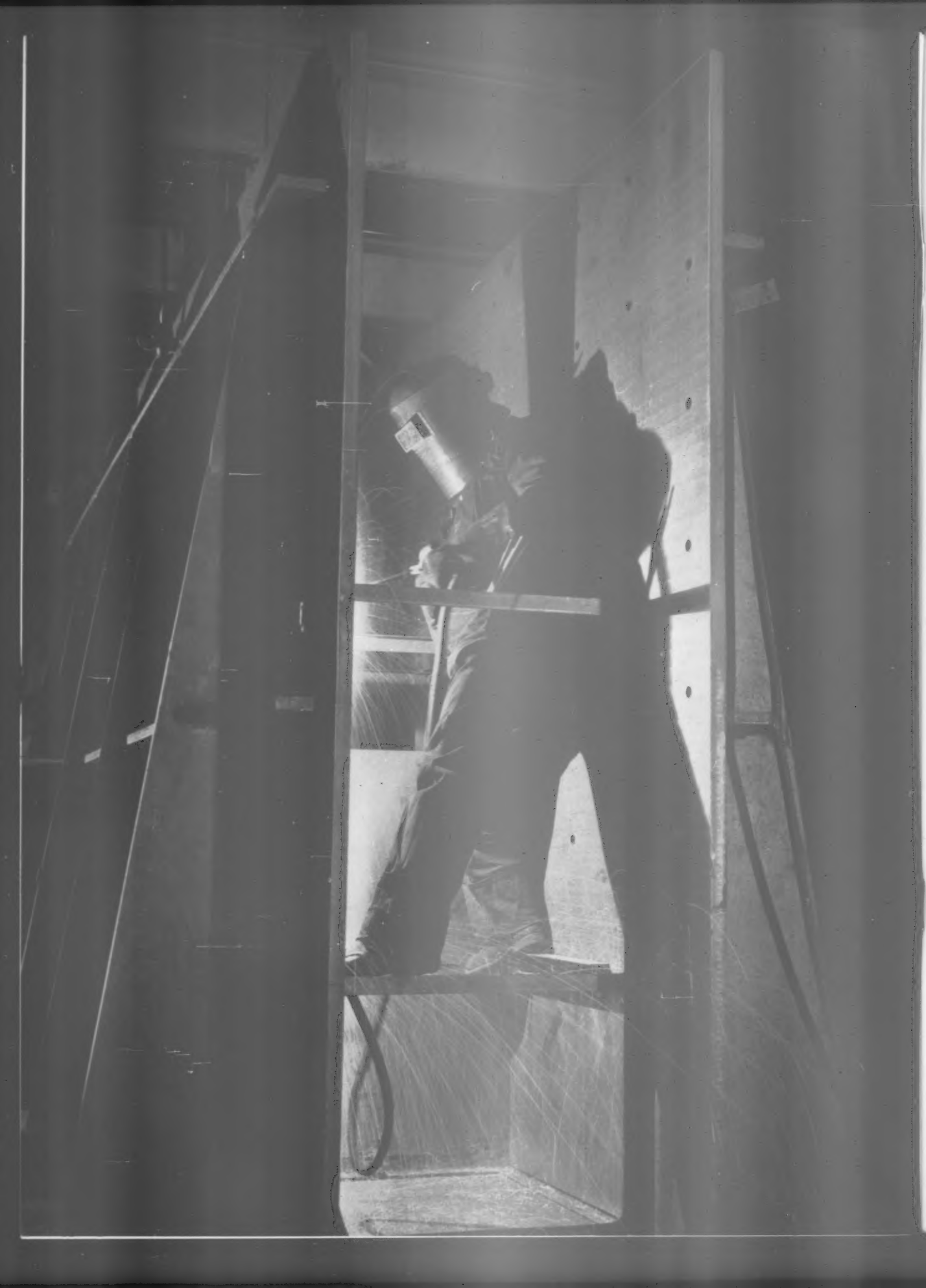

TELEPHONE INTERFERENCE AND ALTERNATOR WAVE SHAPE

Telephone interference from adjacent power lines may have many causes other than the generator. However, there are ways to design a generator to make it least likely to cause interference. There are also ways of keeping interference-creating harmonics from going beyond the powerhouse.

L. T. Rosenberg

ELECTRICAL DEPARTMENT • ALLIS-CHALMERS MANUFACTURING COMPANY

Harmonic voltages and currents are found in nearly all commercial a-c systems, not only because of their presence in the generators but because of the distortion from transformers, rectifiers, and other electrical apparatus. Unless they become too great, these harmonics are not harmful to the power system, but they may induce objectionable noise in nearby telephone circuits.

Other than the magnitude of the generated harmonic voltages, there are several external factors that play roles in most inductive interference cases. The length of the parallel exposure and the proximity of the power lines to telephone lines, the susceptiveness of the telephone circuit, resonance in the power line, ground returns, inadequate transposition, unbalanced capacitance, and many other elements beyond the control of the generator builder have been found to contribute to induced telephone noise.

Weighting curve

Early investigators soon recognized that some sort of measuring stick for the interference effect of a given generator would greatly simplify their research, in addition to paving the way for standards. Accordingly, a series of tests were conducted by different observers between 1914 and 1918. Among other things it was found that, because of the characteristics of both telephone equipment and human hearing mechanism, harmonic voltages of different frequencies, although equal in magnitude, differed widely in their disturbing effects when heard in a telephone receiver.

Based on the assumption that the inductive coupling varied with the frequency, a weighting curve (Fig. 1) was proposed in 1919 to give the relative disturbance level of a given voltage as a function of its frequency. A further assumption was that the interfering effect of several single frequencies, when occurring in combination, would be proportional to the square root of the sum of the squares of their individual interfering effects. Then it was possible to design a network (Fig. 2) which, when a voltage is applied to it, will permit the various component frequencies to pass in proportion to their respective weightings on the curve. The root mean square value of the current passing through this network is then a direct indication of the severity of the interference to be expected from the impressed voltage wave.

If the current passing through this weighting network is divided by the impressed rms voltage, the result is a convenient measuring unit of the potential interference property of the voltage wave. This unit is called the telephone interference factor, usually abbreviated TIF. A current wave may likewise be appraised in this way by passing the current through

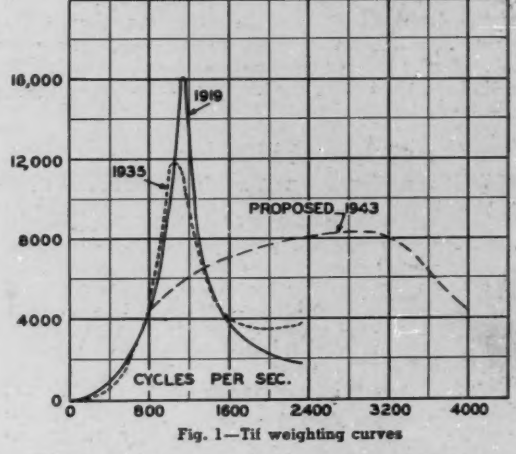

Fig. 1—Tif weighting curves

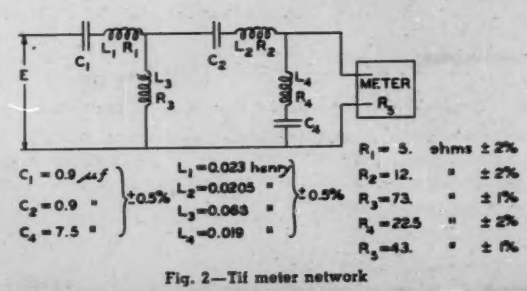

Fig. 2—Tif meter network

AT LEFT: During welding, switchgear frames are held rigidly in position by this special jig. Fabrication method is similar to skyscraper construction, the jig in this case assuring exact duplication of all switchgear frames.

a suitable non-inductive shunt and measuring the TIF of the potential drop.

Instrument developed

The telephone interference factor of a voltage (or current) wave is then the ratio of the square root of the sum of the squares of the products of the individual harmonic voltages (or currents) by their respective weighting factors, divided by the rms value of the voltage (or current). Expressed in symbols:

$$TIF = \sqrt{\frac{\Sigma\,(E_n\,W_n)^2}{\Sigma\,E_n^2}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

The instrument for measuring TIF consists of a network (Fig. 2) conveniently arranged in a case along with a thermo-couple type milliammeter and suitable multipliers. The instrument is designed to measure both the micro-amperes current flowing and the impressed rms voltage.

The present TIF meter has been widely used since its introduction in 1919, but it was based upon data collected before that time, and more complete information has since become available. A paper in 1935 proposed a revised weighting curve, but because of impending changes in telephone equipment at the time the revision was not adopted. Another weighting curve is proposed, which appears to shift the entire region of high TIF values well up into the higher frequency range. Both proposed curves are shown in Fig. 1.

This method of rating a wave has one serious drawback. It assumes that the inductive coupling is proportional to the frequency for all harmonics. However, in a three-phase system the triple harmonics are in phase in the three lines, and their inductive coupling with a grounded neutral may be forty times that for the same current flowing in normal three-phase relationship. For this reason the triple-frequency harmonics are measured separately. This can be done by inserting the TIF meter into an open corner of the delta connection of the windings. The micro-amperes flowing divided by three times the rms phase voltage is then the TIF assignable to the triple harmonics. This value is termed the "residual" component of TIF, as distinguished from the "balanced" component measured between terminals.

Sources of harmonics

While it is perfectly true that the pole face of an electrical machine can be so shaped that the flux distribution will be sinusoidal (Fig. 3), certain practical considerations prevent the full utilization of this fact. In general, the flux form will tend to be flat topped as in Fig. 4; and, when expressed as a Fourier series, it usually will show appreciable odd harmonic components. These are, of course, converted into voltage harmonics in the armature conductors.

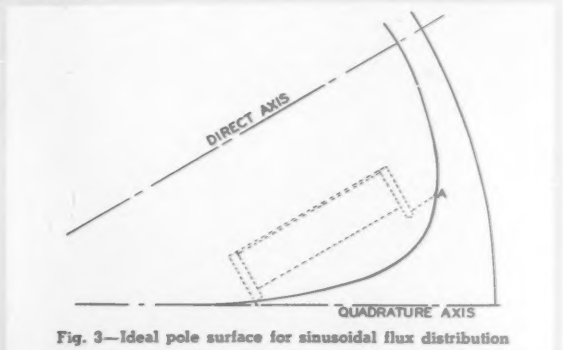

Fig. 3—Ideal pole surface for sinusoidal flux distribution

In order to embed the windings into the stator and rotor surfaces, slots must be provided. Rotor slots cause additional distortion in the flux form, and stator slots cause a pulsation in the flux because of the changing reluctance of the air gap with different rotor positions. The armature slotting is perhaps the most common cause of inductive interference from a-c generators. The harmonics generated are of order, twice the number of slots per pole $\pm$ 1.

The presence of saturation in certain parts of the magnetic circuit may also tend to distort the flux form. The increased reluctance of the stator teeth at high densities causes a flattening of the peak of the wave. Similar effects may occur in the rotor of a turbine-generator in which the roots of the pole centers and adjacent teeth sometimes saturate before other parts.

Load changes TIF

Under load, the stator current modifies the flux form. The combined effect upon the harmonic voltages will depend upon the magnitude and the power factor of the load since the displacement angle of the rotor in relation to the stator terminal voltage is a function of these two variables. Tests on both inductive and non-inductive loads on a number of machines revealed that in many cases the no-load TIF may be reduced 30% or more at rated load when the load is reasonably well balanced between the different phases. If the load is unbalanced, voltage harmonics may be generated by space fundamental mmf waves rotating at speeds different from that of the rotor.

Fortunately, there are a number of ways in which the harmonics generated in the inductors can be reduced in magnitude before they appear at the generator terminals. Harmonics in the flux form will generally be badly out of phase in the different coils of a phase belt, while the fundamental voltage is but slightly out of phase. The reduction factor for the nth harmonic as a result of this belt differential effect will be:

$$K_{bn} = \frac{\sin\left(n\frac{S}{\Phi}\times\frac{\delta}{2}\right)}{\frac{S}{\Phi}\times\sin\left(\frac{n\delta}{2}\right)} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where S = no. of slots/pole

Φ = no. of phases

δ = elec. angle between slots

n = order of harmonic

Values of K_{bn} are shown graphically in Fig. 5.

Harmonics of space fundamental distribution either pulsating or rotating at n times synchronous speed are reduced by the same amount as the fundamental; i.e., $n = 1$ in this equation. The slot harmonics fall into this category and, when expressed in percent of the

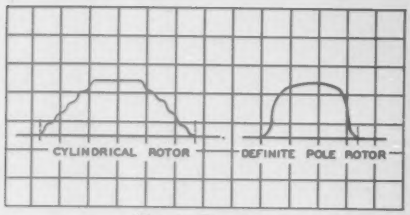

Fig. 4—Flux forms

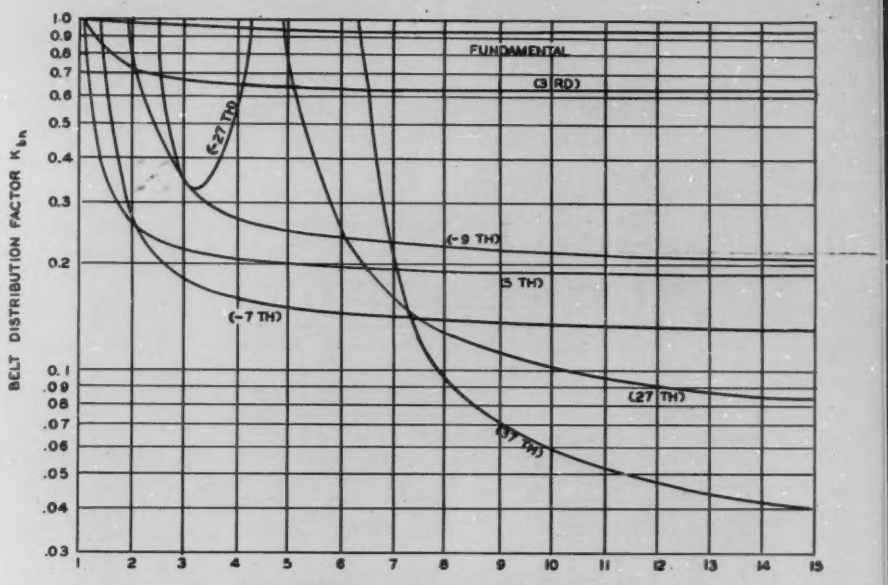

Fig. 5—Belt distribution factor

fundamental, are totally unaffected by the belt differential factor.

Creeping winding

The most effective manner of dealing with the slot harmonics is by using a "creeping winding." A fractional number of slots per pole are employed, resulting in a slight circumferential shift of corresponding slots under adjacent poles. A perfectly balanced winding is possible but some distortion in the stator mmf wave results because the number of coils in all phase groups is not the same. The reduction factor for a creeping winding may be expressed as

$$K_{Cr.n} = \frac{\sin\left(n\frac{S}{\Phi}\times\frac{\delta}{2}\right)}{y\sin\left(\frac{n\alpha}{2}\right)} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

where y = the numerator of improper fraction (reduced to lowest terms) expressing the number of slots/phase group.

α = elec. degrees/phase belt $\div$ y

Fig. 5 may be used for the creep reduction factor by using y as abscissa instead of S/Φ.

In slow speed machines, the creeping winding may result in a tremendous reduction in TIF. However, the reduction is the result of a carefully planned shifting of the coils into exactly the right positions. When dampers with open slots are employed, the rotor poles must be carefully assembled. If they do not fall into their correct positions, a considerable increase in TIF may result. One case is on record where the TIF of a machine with a creeping winding was reduced from 80 to 20 by a more precise spacing of the rotor poles.

Short-pitched coils

Perhaps the best known means of limiting harmonic voltages is by using short pitched stator coils. The reduction factor for the nth harmonic is:

$$K_{pn} = \sin\frac{np\pi}{2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where p = per units coil pitch.

Values of K_{pn} are shown in Fig. 6.

Here again, as in the case of the belt differential factor, only space harmonics are affected, and there is no reduction in the slot harmonics if expressed in percent of the fundamental. The triple-frequency harmonics can all be nullified if a pitch of ⅔ is used. In practice, a coil pitch ranging from 0.75 to 0.90 is usually desirable for a number of reasons. Moreover, the use of different coil pitch values enables the designer to secure the precise operating densities for a given rating that will make for best all-around performance. In turbine-generators, if the triple harmonics threaten to be troublesome, they may also be eliminated by making the slotted portion of the rotor equal to ⅔ of the total rotor surface. This avoids the necessity of a ⅔ pitch stator coil.

Skewed poles

Another effective way of dealing with harmonics of higher order is to skew either the stator slots or the rotor poles. The reduction factor is shown in Fig. 7 and may be expressed as:

$$K_{sk.n} = \frac{\sin\frac{n\lambda}{2}}{\frac{n\lambda}{2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

where λ = elec. angle of skew.

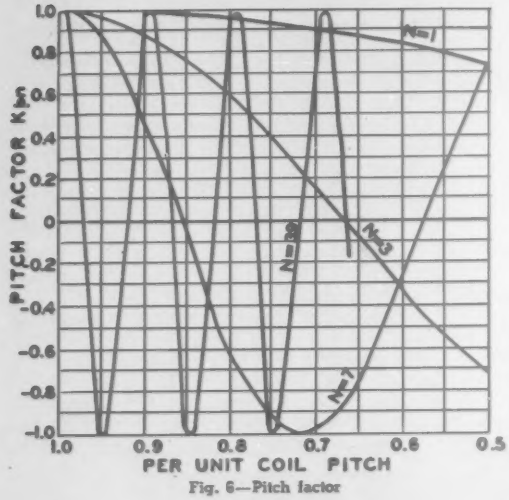

Fig. 6—Pitch factor

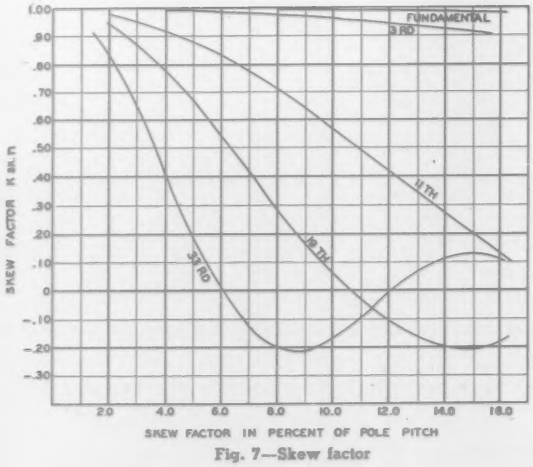

Fig. 7—Skew factor

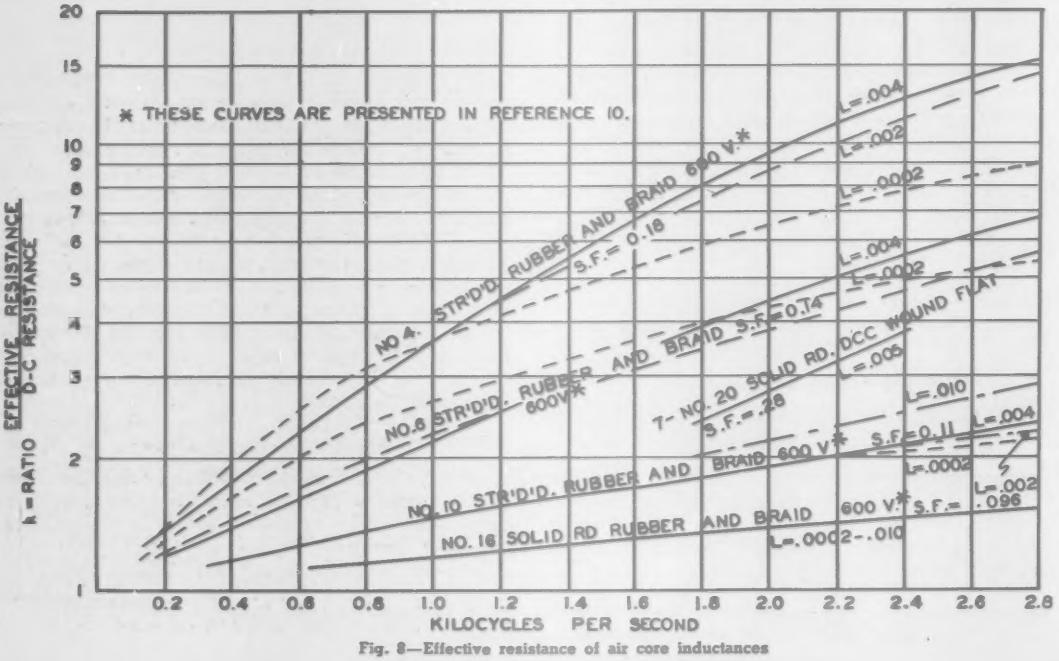
* THESE CURVES ARE PRESENTED IN REFERENCE 10.
k = RATIO EFFECTIVE RESISTANCE / D-C RESISTANCE
NO 4. STR'D'D. RUBBER AND BRAID 600 V.*
S.F.= 0.18
NO.8 STR'D'D. RUBBER AND BRAID S.F.=0.14
600V.*
7- NO. 20 SOLID RD. DCC WOUND FLAT
S.F.=.28
NO. 10 STR'D'D. RUBBER AND BRAID 600 V.* S.F.=0.11
NO. 16 SOLID RD RUBBER AND BRAID 600 V.* S.F.= .096
L=.004
L=.002
L=.0002
L=.005
L=.010
KILOCYCLES PER SECOND

Fig. 8—Effective resistance of air core inductances

The skew factor applies primarily to space harmonics, but the slot harmonics can also be suppressed because the pulsation in reluctance of the air gap is reduced. If the skew is made one slot pitch, the slot harmonics disappear.

It is well known that, in star-connected three-phase machines, the triple harmonics of the flux wave do not appear between terminals. Similarly the voltage of the balanced harmonics are reduced to 86.6% of their algebraic sum for the two legs in series. The reduction factor expressing the effect upon the nth harmonic of the manner in which the phases are connected is:

$$K_{cn} = \frac{\sqrt{(\Sigma \sin n\theta_m)^2 + (\Sigma \cos n\theta_m)^2}}{\Phi_1} \quad \ldots\ldots (6)$$

where θ_m = displacement angle of phase m

Φ_1 = no. phases in series between terminals.

Corrective measures

After a machine is completed it is not easy to change the shape of the voltage wave. The pitch of the stator coils might be changed if new coils are manufactured. In definite-pole machines, the poles might be machined or skewed. If new punchings are made, the slots can be changed and even skewed. Such changes as these usually run into considerable expense, and when the possible improvement is carefully considered the cost is seldom justifiable.

A more practical solution, particularly when the disturbance is due to one or two prominent harmonics, is the application of a selective device external to the machine. External devices for suppressing interference may be either of the "resonant" or "non-resonant" type. Because of the sharpness with which the resonant type can be tuned, it is well suited for the reduction of individual harmonics.

Two common types of resonant devices are in general use. For harmonics that are a multiple of three on a three-phase system, the series resonant circuit may be employed in the neutral connection to ground. It consists merely of a reactor and a capacitor in parallel and is sometimes called a wave trap. When the inductive reactance of the reactor is equal to the capacitive reactance of the condenser at a given frequency, the circuit is resonant to that frequency, and it will offer a high impedance to the flow of current of that frequency into the neutral connection.

Since, as previously pointed out, the triple frequency currents must flow out on the three lines in parallel and back through the neutral connection, any given triple harmonic current can be effectively reduced by such a device. Two or more harmonics can be suppressed by the use of separate wave traps, each tuned for one frequency and connected in series.

Resonant shunt

The other common type of resonant device consists of a capacitor and a reactor in series. It is best suited for reducing non-triple harmonics and is applied directly across the generator terminals. When properly tuned for a given frequency, this circuit, known as a "resonant shunt," gives a low impedance short circuiting path for the harmonic of that frequency. A three-phase machine requires a separate shunt for each phase.

Since the effectiveness of a resonant shunt depends upon a number of factors, its design must be based upon a complete knowledge both of the generator and the power system. The following data are necessary:

a. The exact frequency and magnitude of the harmonics to be reduced.

b. The necessary reduction in these harmonics.

c. The magnitude of other significant harmonics present.

d. Internal generator impedance to the harmonics under consideration.

e. Impedance of system at these same frequencies.

This information can best be obtained from actual measurements of the system with a harmonic analyzer. The generator impedance can be obtained by short circuit and open circuit tests, or more accurately with a temporary resonant shunt tuned for each individual harmonic.

The frequency at which the reactor and capacitor will be resonant is

$$f_n = \frac{1}{2n\sqrt{L\,C}} \quad \ldots\ldots (7)$$

Obviously any value may be selected for C, provided the corresponding L satisfies equation (7). A commonly accepted method of arriving at values of L and C is first to assume a given ratio of reactance to resistance for the reactor and then to select a condenser which will carry the short circuited harmonic current as well as all of the fundamental current that is likely to flow through it. With C established, L can be determined.

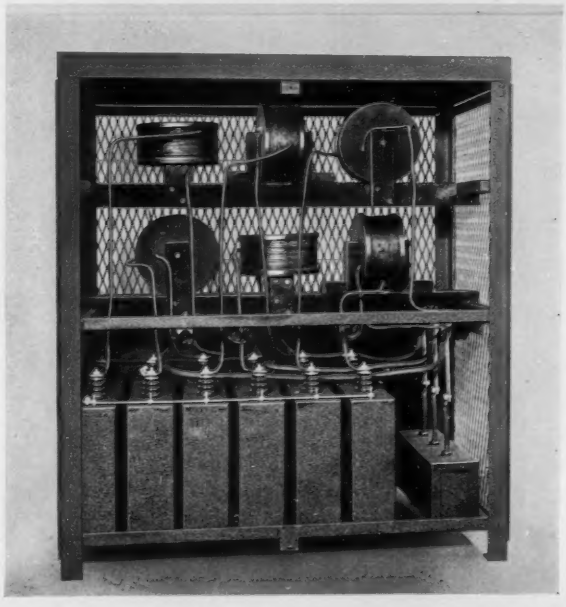

Fig. 9 — Interior view of resonant shunt assembly for 1000 kw, 2300 volt, 3-phase alternator.

What is possibly a more direct solution can be based upon the total cost of the device. The total cost per phase of the coil and capacitor for a resonant shunt can be shown to be

$$\$_T = \$_{\mu f} \times \frac{C}{3} \times 10^6 + \$_f \times 6140 \left(kL\ (B_n - 1) \right)^{2/2} \quad \ldots (8)$$

where $\$_{\mu f}$ is the cost in dollars per mfd of condensers of the voltage rating required.

$\$_f$ is the cost in dollars per pound of copper for the inductance coils.

C is the capacitance of the condensers.

L is the inductance of the coils.

B_n is the required effectiveness ratio of the shunt.

$$= \frac{\text{nth harmonic voltage without shunt}}{\text{nth harmonic voltage with shunt}}.$$

Z_{tn} is the combined parallel impedance of the generator and system to nth harmonic.

k is the coil ratio of a-c to d-c resistance of the type of coil to be selected at frequency f_n (Fig. 8).

Replacing L by $\frac{1}{4\pi^2 f_n^2 C}$ from equation (8) and differentiating with respect to C we get

$$\frac{d\ \$_T}{d\ C} = \frac{\$_{\mu f} 10^6}{3} - \frac{37.1\ \$_f}{f_n^3\ C^{5/2}} \left[\frac{k\ (B_n - 1)}{} \right]^{1/2} \quad \ldots\ldots\ldots 9$$

Equating to zero we find the capacitance for minimum cost:

$$C = \sqrt[5]{\left(\frac{111.1\ \$_f}{f_n\ 10^6\ \$_{\mu f}} \right)^2 \left(\frac{k\ (B_n - 1)}{Z_{tn}} \right)^3} \quad \ldots\ldots\ldots (10)$$

Before using this value, however, it is well to check the current rating of this condenser to make sure it will carry both the harmonic and fundamental currents.

Condensers not accurate

The inductance required can readily be calculated from equation (7). The calculated value of inductance should not be relied upon, however, because commercial capacitors have considerable tolerance in their capacitance. The final adjustment of the number of turns on each coil should be made by tuning it with its capacitor. The harmonic analyzer and a low frequency oscillator are very useful here.

When a resonant shunt is applied to a generator for the suppression of the nth harmonic voltage, there is a frequency below f_n corresponding to resonance with the generator inductance at which any generated harmonic will be amplified. In a well designed shunt this sub-resonance point will occur at some frequency where there is no appreciable generated harmonic.

In practice, two or more resonant shunts may be compactly arranged in a steel rack as shown in Fig. 9. Two three-phase delta connected shunts, designed in accordance with the foregoing relations, were employed for the suppression of 35th and 37th harmonics in a 1000 kw, 2300 volt generator. Fused cutouts, not visible in the photograph, are mounted on a panel at the front of the rack for short circuit protection and for disconnecting the shunts. The discharge coil at the lower right protects attendants. Test data are shown in Table I, while Fig. 10 shows the shunt impedance as a function of the number of turns on the coils. Individual and combined shunt impedances as a function of frequency are shown in Fig. 11.

Harmonic n	Open circuit T-T voltage E_n, volts to neutral	Generator internal impedance ohms per phase	Remaining harmonic voltage (volts to neutral) at no-load	Effectiveness ratio of shunt at no-load B_n	Shunt current, amperes per line
1.0	1300.		1300.		3.18
29	0.79		2.17	0.36	
31	0.68		0.54	1.26	
35	20.10	5.55	1.45	13.9	3.36
37	16.60	6.50	0.96	17.2	2.40

List of symbols

B_n = Effectiveness ratio of a selective device

C = Capacitance of condenser in selective device

E_n = Generated nth harmonic voltage

f_n = Frequency of nth harmonic

K_{bn} = Belt reduction factor for nth harmonic

K_{cn} = Connection factor for nth harmonic

$K_{cr.n}$ = Creep reduction factor for nth harmonic

K_{pn} = Pitch reduction factor for nth harmonic

$K_{sk.n}$ = Skew reduction factor for nth harmonic

k = Ratio of effective resistance to d-c resistance of inductance (Fig. 8)

L = Inductance of reactor in henrys

n = Order of any given harmonic

p = Per unit coil pitch

r_{pn} = Effective resistance of inductance coil to nth harmonic

S = Number of stator slots per pole

TIF = Telephone interference factor

W_n = Weighting factor for nth harmonic

y = Numerator of improper fraction (reduced to lowest terms) expressing the number of slots per phase group

Z_{tn} = Combined parallel impedance of generator and line to nth harmonic

α = $\left(\frac{1}{y}\right)$ times the number of electrical degrees per phase belt

δ = Electrical angle between adjacent slots

θ_m = Phase angle of phase m

λ = Electrical angle of skew

Φ = Number of phases

Φ_1 = Number of phases in series between terminals

$\$_{\mu f}$ = Cost of capacitors in dollars per microfarad

$\$_f$ = Cost of inductance coils in dollars per pound of copper

$\$_T$ = Total cost of coil and capacitor for one phase

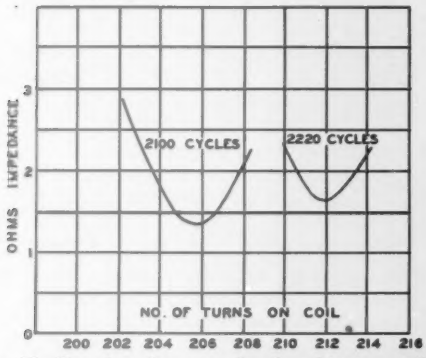

Fig. 10—Shunt impedance as a function of turns on coils

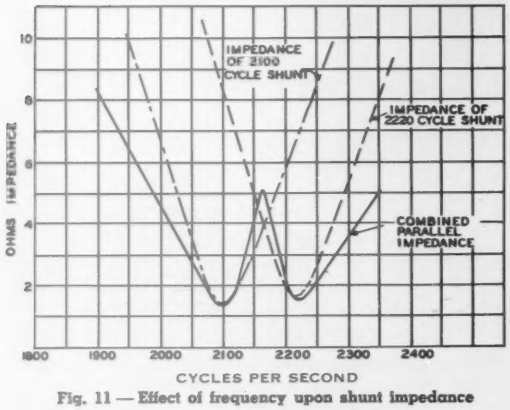

Fig. 11 — Effect of frequency upon shunt impedance

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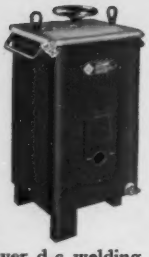


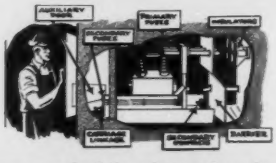
New Alternating Current Ampac "200" Welder

An important new forward step in alternating current welding in the form of the new Ampac "200" welder has just been announced. Added to many advantages of a-c over d-c welding, a number of distinctive features are also claimed for the new Ampac to establish it as an important factor in the rapidly growing trend to a-c welding in the nation's war industries.

Described as the welder with the ideal operating curves, the Ampac "200" automatically gives the operator correct voltage for the continuous range of currents available, rather than using an almost constant voltage at all current settings. This adjustment not only makes welding easy at low currents because of the high striking voltage, but saves power when welding at high currents because the voltage is low.

Other special design and operating features of the Ampac "200" include the new integrated reactor-transformer construction which provides the high, yet safe voltage for easy welding at low currents; active duty from every line of flux . . . assured by reactor coils which surround the variable air gap; and simplified construction using fewer working parts, cutting maintenance down to routine lubrication twice a year.

Characteristic of a-c welding in general are the lower original cost, less power consumption and easier welding.



Carriage-Mounted Transformers

Making the maintenance man's job safer and easier inspired the recent redesigning of drawout potential transformers for metal-clad switchgear of the type widely applied in central stations, larger unit-substations, and for use in various war industries. Hereafter all switchgear of 100,000 kva capacity or over will be equipped with the newly designed, carriage-mounted potential transformers.

For inspection, changing of fuses, cleaning or other maintenance operations on the new switchgear units, all that the maintenance man need do is open the transformer compartment door, and the door actuates the carriage, mounted on ball-bearing wheels. As the carriage is drawn out, the transformers are automatically de-energized, and primary fuse elements are easily reached. However, unless the transformer compartment door is open, fuse elements are inaccessible.

For further, more detailed information regarding these new products, write the Editors of ELECTRICAL REVIEW.

TRANSFORMERS THAT ONLY WHISPER

Noisy transformers in residential districts invite complaints. Now there are methods of accurately measuring noise and even predicting the noise level of a transformer before it is built.

L. C. Aicher

TRANSFORMER DIVISION • ALLIS-CHALMERS MANUFACTURING COMPANY

Almost everyone has heard the hum that emanates from a transformer. Ordinarily the hum or sound from the usual distribution transformer found in residential districts is so low in intensity that it is unnoticed. However, as electrical loads increase, it becomes necessary to replace the smaller transformers with larger ones and occasionally it is even necessary to install a rather large substation in or adjacent to residential districts.

As transformers become larger, the sound level becomes more prominent, and sometimes it becomes disturbing. This is especially true during night time when the background noise level is low. It is good engineering to consider the noise aspect of a transformer in the planning stage rather than after complaints make a noise abatement program necessary.

Noise and sound

Design engineers understand the origin of transformer noise but unfortunately they are limited in their ability to control it. This is one of the engineering problems that requires a solution which is not only technically practicable but also economically satisfactory.

The noise output of a transformer depends upon a number of electromagnetic and mechanical factors which also influence the electrical characteristics of the transformer. Variations of these electromagnetic and mechanical properties are limited by the necessities of efficiency, reactance, cost, and thermal dissipation.

Sound is produced by vibratory motion. The most familiar magnetic noise is produced when an alternating magnetomotive force is applied to a ferro-magnetic circuit having an air gap in which the opposing surfaces are not kept properly separated. The magnetic pull will vibrate punchings at double the applied frequency, and the amplitude of vibration will depend upon how solidly the joints are held. Higher harmonics may be produced because the flux wave is seldom exactly sinusoidal. However, the noise from this source in a well built transformer is negligible.

Another potential source of noise in a transformer is the magnetic forces around and between the windings caused by load currents. If the load-current wave form is substantially sinusoidal, these vibrations also are double the impressed frequency. However, calculations show that the amplitude of coil vibration from full load current for an average transformer is quite small, and the noise is near the threshold of hearing. This is confirmed by tests which indicate that changing the load has no appreciable effect upon the noise level produced by the core at no load. A further confirmation is that during short circuit impedance tests, noise and vibration of the coils are inaudible.

Magnetostriction, the noisemaker

In 1842 Joule discovered that an iron rod changed its length when subjected to a magnetic field whose direction was parallel to the axis of the rod. This is one of the many effects exhibited by all ferromagnetic materials and it is known as magnetostriction. This phenomena has been extensively studied by many engineers and physicists because it undoubtedly has an important bearing on the theory of magnetism.

It has been definitely established that magnetostriction of the core steel is responsible for nearly all of the noise emitted by a transformer.

Little is known about magnetostriction of silicon core steel and how it can be controlled. Some materials lengthen while others shorten with an increase in magnetization. Most transformer core steel lengthens in a direction parallel to the flux lines and contracts at right angles to the flux lines as magnetization is increased. Some core steels shorten parallel to the flux lines until saturation is approached, then tend to lengthen. An average magnetostriction curve for modern silicon core steel of transformer grade is shown in Fig. 1. For the flux densities used in the core of modern transformers, magnetostriction takes the form at an elongation for both halves of the flux wave.

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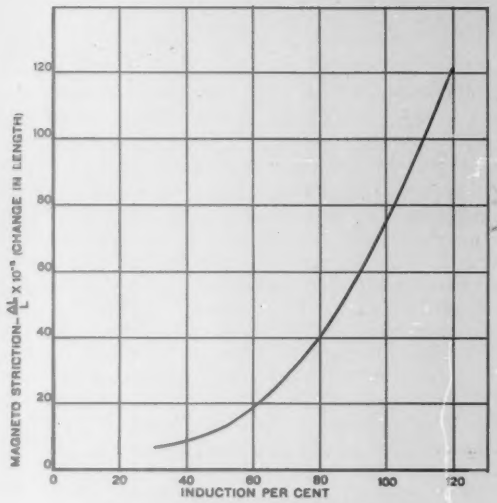

Fig. 1—Magnetostriction vs. induction.

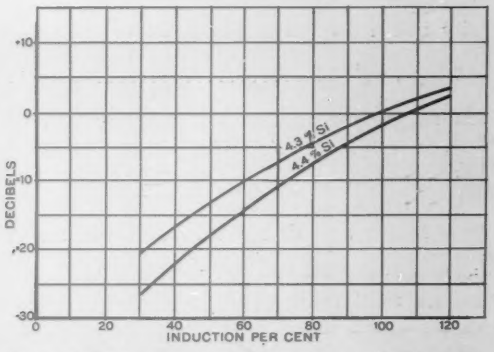

Fig. 2—Sound intensity vs. induction for core steels of different silicon content.

Considerable investigation has been done on the effect of silicon content on magnetostriction. Some of these results are shown in the curves in Fig. 2. Unisolated factors in addition to chemical composition influence magnetostriction, for consistency of results is an exception rather than a rule. It has been found that steel containing 6 to 6½ percent silicon is least affected by magnetostriction. The advantageous magnetostrictive qualities of a high silicon content steel cannot be utilized at the present because the steel's brittleness prohibits its practical use.

Within a certain range, the elongations due to magnetostriction vary approximately with the 2.5 power of the flux density, B. With a sinusoidal flux wave we have,

$$\frac{\Delta L}{L} = CB^{2.5} \sin^2 wt$$
$$= C_1 B^{2.5} \cos 2wt \qquad (1)$$

where C and C_1 are constants.

This indicates that a sinusoidal flux produces sinusoidal vibrations of twice the flux frequency. However, it is known that in addition to this vibration of fundamental frequency the core vibrates at higher frequencies that are harmonically related. The exact explanation for these harmonic vibrations is not yet available. The number and magnitude of these harmonic vibrations depends upon the nature of the steel and the flux density. It therefore can be said that a given steel has a noise spectrum (Fig. 3) for each flux density.

Magnitude of dimensional changes

The dimensional changes of silicon steel under electromagnetic influence are almost atomic in size, as can be seen by comparison with the approximate diameter of an atom, 8×10^{-7} inches.

Laminations that are straight, free to elongate, and symmetrically clamped deflect in proportion to their length. All deflections in a single phase transformer core occur simultaneously. Vibrations of the core of a three-phase transformer are complicated by the phase relations of the fluxes in the different parts. All parts of a three-phase core are not at maximum flux density simultaneously.

Vibrations can be reduced somewhat by tightly clamping the core. Yoke end plates must produce uniform clamping action throughout their length to prevent vibration perpendicular to the plane of the laminations. Unusually tight clamping at two points along a yoke end plate causes the laminations to bow at intermediate points when magnetized, thus producing vibrations at right angles to the plane of the laminations.

Let us assume a lamination 80 inches long is magnetized with 100 percent flux as in Fig. 1. At this induction $\frac{\Delta L}{L} = 77 \times 10^{-6}$ and for 80 inches $\Delta L = 80 \times 77 \times 10^{-6} = 61.6 \times 10^{-6}$ inches. The mechanical force required to elongate the core the same amount is numerically equal to that which would be necessary to offset the elongation due to magnetostriction. A core having an area of 1000 square inches has a mechanical force,

$$P = \frac{AE\,\Delta L}{L} \qquad (2)$$

$$= 1000 \times 30 \times 10^{-6} \times 77 \times 10^{-6} = 23{,}100 \text{ lbs.}$$

It is evident that quite sizable restraining forces are required to counteract the core elongation tendency. In most transformer cores this restraining force is provided by friction produced from clamping the core at right angles to the plane of the laminations.

Sound measurement

It is the sensation produced in the ear that is of ultimate interest to the acoustician. As a sound receiver, the characteristics of the ear can be approximated by an electro-mechanical network such as a sound level meter.

There are two methods of noise measurement, the subjective and the objective method. The use of a subjective method implies that the characteristics of the ear are difficult to simulate, and accordingly the ear is used as part of the measuring equipment. In the objective method, the characteristics of the ear are

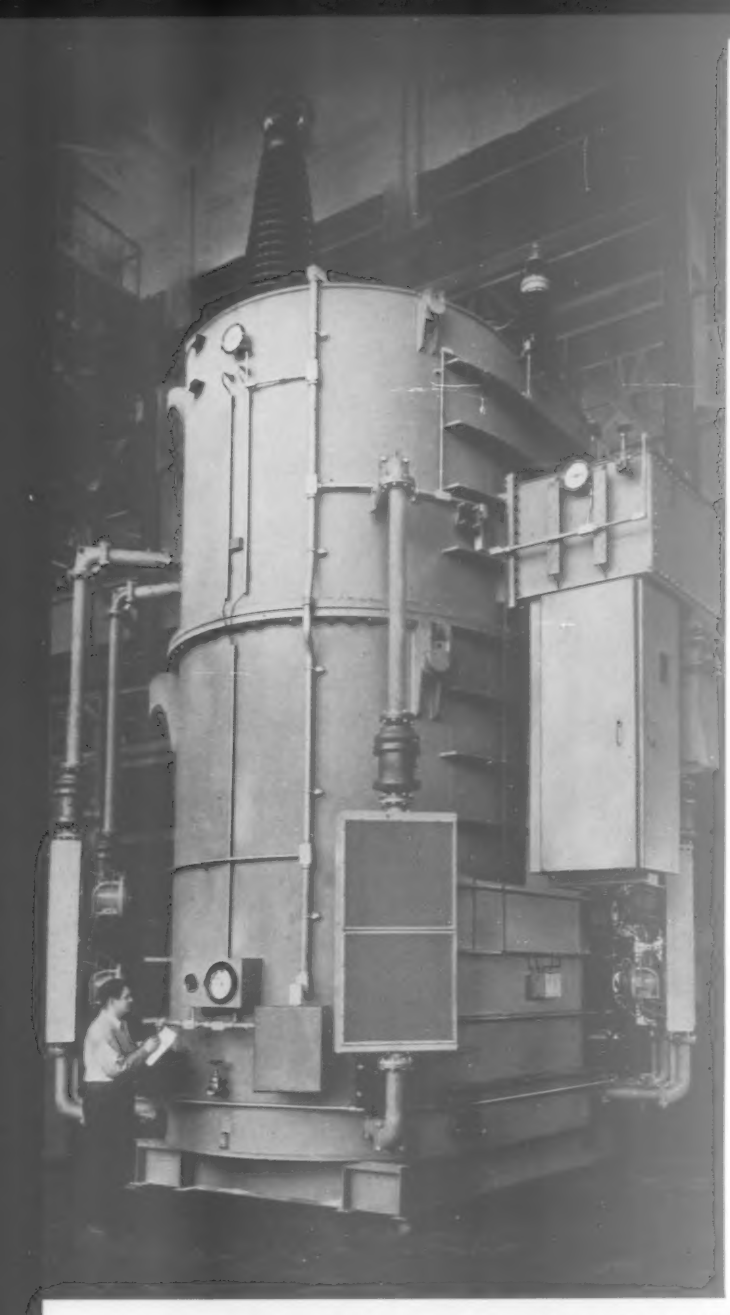

Fig. 2 — With its design based on the methods described in this article, even a transformer as large as the one shown above proves on tests before leaving the factory that the noises emanating from it in operation will not be objectionable.

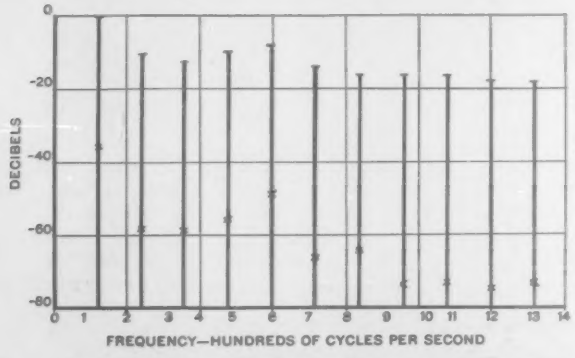

Fig. 3—Frequency spectrum of typical transformer core steel relative to strongest component. (– = 100% induction x = 80% induction)

simulated by electrical circuits. The subjective method requires considerable time and patience, and introduces a great strain on the observers when many observations are made. For these reasons the objective method is preferred.

An objective sound level meter[1] consists of a microphone, amplifier, attenuators, and an output meter, usually calibrated in decibels. A psychological law states that the increase of a stimulus necessary to produce a barely discernible increase in the resulting sensation bears a constant ratio to the total stimulus. Referred to the ear, it means the loudness is closely associated with the logarithm of intensity. The unit of intensity level is the "bel," a rather large unit, which has been subdivided into tenths called "decibels." The number of decibels denoting the ratio of two amounts of power P_1 and P_2 is ten times the logarithm to the base ten of this ratio. Thus

$$n = 10 \log_{10} \frac{P_1}{P_2} \text{ db} \quad \ldots\ldots(3)$$

Likewise if I_1 and I_2 represent two values of sound intensity and n the number of decibels,

$$n = 10 \log_{10} \frac{I_1}{I_2} \text{ db} \quad \ldots\ldots(4)$$

This suggests a measure of intensity level, I.L., when $I_2 = I_0$, commonly referred to as reference intensity.

Thus

$$\text{I.L.} = 10 \log_{10} \frac{I}{I_0} \text{ db} \quad \ldots\ldots(5)$$

At the present the reference intensity is 10^{-16} watt per square centimeter.

The frequency response of the meter is flat within the audio-frequency range, but additional weighting networks are usually incorporated in the instrument to simulate the response of the human ear at various sound levels. Unfortunately, modern sound level meters, even though they meet rather rigid performance standards, are somewhat limited in perfection of details influencing noise levels. Present day sound meter standards allow a total tolerance band of from 5 to 16 decibels, depending upon the frequency composition of the sound under observation.

There are three frequency weighting characteristics recognized by the A.S.A. These are designated as Curve A, B, and "Flat," which correspond in weight according to the 40, 70, and "Flat" decibel equal loudness contours.[2] Which frequency weighting should be used in measuring transformer noise levels depends upon the background or ambient noise level. Most of the transformers that are installed where noise is of importance will probably be located in an ambient noise level between 35 and 50 db. In such cases the 40 db frequency response curve is preferable.

Predicting noise level

If the vibrations generated in the core are all transmitted through the oil without attenuation and if all vibrations of the tank wall are forced, then the noise level of a transformer can be estimated.

1 See American Standards Association Standard Z24.3, Sound Level Meters.
2 See American Standards Association Standard Z24.2, Noise Measurement.

The amplitude of the core vibrations at fundamental frequency can be estimated from the magnetostriction curve and the dimensions of the magnetic circuit involved. From this amplitude the excess pressure of the air wave in dynes per sq. cm. and the corresponding decibel noise level can be calculated. In order to obtain the noise level corresponding to the 40 db frequency response for the harmonic spectrum present, a correction must be applied which is a function of the flux density at which the magnetic circuit is worked. The actual noise level of the transformer measured a certain distance from the periphery of the transformer, say one foot, can be expected to be less than the calculated figure because of (a) the attenuation of the core vibrations through the oil, (b) the attenuation through the tank wall, (c) the attenuation in air between the transformer and microphone, and (d) the non-linear attenuation of the higher frequency vibrations.

A transformer designer's interpretation of Fig. 1 is that a transformer's sound level is a function of induction.

The intensity of sound is related to displacement amplitude thus

$$I = 2\pi n^2 a^2 DV \quad \ldots\ldots (6)$$

in which:

n = frequency in cycles per second

a = displacement amplitude (equal to ΔL) cm.

D = density of the medium in which the sound waves are set up, gm/cm³.

V = velocity of sound in the medium, cm/sec.

This intensity relationship can be substituted into Eq. 5 to get the relationship of sound with displacement amplitude. The curve of this translation is most practical as a correction curve, based upon a reference point arbitrarily chosen as 100% induction. The expression for decibels now becomes

$$db = 20 \log_{10} \frac{\Delta L}{\Delta L_0} \quad \ldots\ldots (7)$$

which when applied to the data of Fig. 1 produces Curve A of Fig. 4, assuming sinusoidal flux at fundamental frequency. This curve was obtained on a strip sample. Curve B is the average of a number of finished transformers obtained by test, weighted to the 40 db response. The deviation, while quite small, is due to the harmonic composition and the non-linear attenuation of the higher harmonics which appear at the higher inductions.

Sound vs. weight

The geometry of large power transformers is such that core dimensions in directions other than those parallel to the base are also large. Consequently, there will also be generated noise that will be combined with that produced by the laminations whose radiations are directed to the tank wall.

A transformer can be considered as a point source of sound, radiating approximately hemispherical sound waves, except as modified by the directional characteristics of the unit.

A transformer with a given induction in the core produces at the outside of the transformer a sound intensity I, proportional to the square of the amplitude of vibration. The amplitude of vibration due to magnetostriction is proportional to the core length L, so

$$I = K_1 L^2 \quad \ldots\ldots (8)$$

where K_1 is a constant.

For transformers of similar proportions, the core weight W is proportional to the cube of the core length, thus

$$W = K_2 L^3 \quad \ldots\ldots (9)$$

where K_2 is a constant. From this equation

$$L = \frac{W^{1/3}}{(K_2)^{1/3}}$$

and when substituted into Eq. (8)

$$I = \frac{K_1 (W)^{2/3}}{(K_2)^{2/3}} = K_3 W^{2/3} \quad \ldots\ldots (10)$$

where $K_3 = \frac{K_1}{(K_2)^{2/3}}$

Upon substituting Eq. (10) into Eq. (5), a measure of transformer sound level develops.

$$db = 10 \log_{10} \frac{I}{I_0} = 10 \log_{10} \frac{K_3 W^{2/3}}{I_0}$$

$$= 10 \log_{10} \frac{K_3}{I_0} + \frac{20}{3} \log_{10} W$$

$$= K_4 + 6.67 \log_{10} W \quad \ldots\ldots (11)$$

where $K_4 = 10 \log_{10} \frac{K_3}{I_0}$, which is a constant when the reference intensity I_0 is constant.

It is evident that changing the reference level does not change the slope of the curve, but only its displacement from an arbitrary datum.

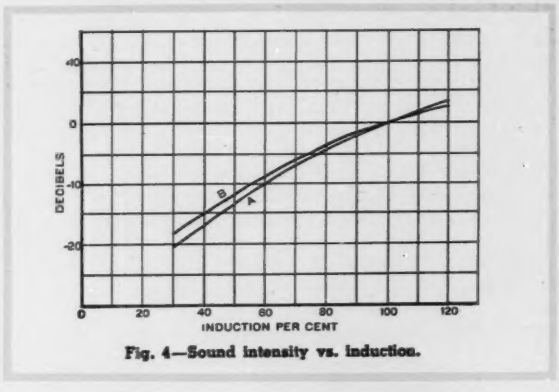

Fig. 4—Sound intensity vs. induction.

Not all modes in which a transformer core can vibrate are attributable to magnetostriction alone. The core is a mechanical structure that can have several natural frequencies and at each of these frequencies the core will vibrate in a particular manner. The tank may also have natural frequencies, as may the appendages like radiators, external operating shafts, mechanism housings and instruments.

If one or more of these natural frequencies happens to equal the sound frequency caused by magnetostriction, resonance occurs and the sound level will probably be raised. In such complicated structures it is not easy to predetermine these natural frequencies.

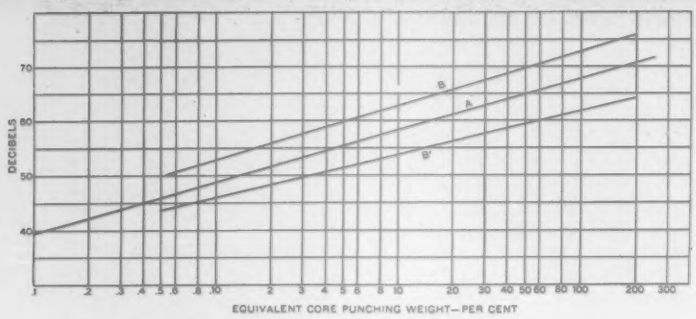

Fig. 5—Audio noise vs. equivalent core punching weight.

The larger the physical size of a transformer, the greater the number of natural frequencies that can exist. This suggests as an addition to Eq. (11), an average measure of the resonant conditions that exist. The equation then is

$$db_w = K_4 + 6.67 \log_{10} W + K_5 \log_{10} \frac{W}{W_0} \quad \ldots\ldots (12)$$

in which K_5 is a constant and W_0 is the weight of the transformer core of proportions where resonance is negligible.

A theoretical evaluation of the factors making up K_4 in the above equation is extremely difficult, so empirical factors are used instead. The curve of Fig. 5 has been arrived at by measuring many transformers of a variety of weights and proportions. Curve A is a plot of the above equation and curves B and B′ indicate the tolerance. This tolerance includes discrepancies due to unlike proportions, variations in magnetostriction of the steel, abnormal resonance phenomena, mixtures of single-phase as well as three-phase transformers, measurement errors, slight meter calibration errors over a period of years, and the extraneous effects of ambient levels and nearby obstructions to an infinitely free sound field.

Sound vs. induction

Few power transformers are designed with an induction exactly equal to the reference induction. Any adjustment for this departure from reference induction should take into account the decibel correction versus induction of curve B, Fig. 4. This curve is nearly quadratic. If all parts of the core operated at the same induction, it would be an easy matter to make corrections in accordance with curve B, Fig. 4. However, few power transformers are designed with equal induction in both the tongue and yoke core material. Therefore it is desirable to have a method to calculate a mythical or equivalent core operating at reference induction and of such weight as to produce the same sound level as the real core. Assuming curve B, Fig. 4 to be quadratic, makes

$$\frac{\Delta L}{L} = CB^2 \quad \ldots\ldots (13)$$

Substituting this in Eq. (7) gives

$$db_B = 40 \log_{10} \frac{B}{B_0} \quad \ldots\ldots (14)$$

If in Eq. (12) a weighting or equivalence factor "F" is allowed to operate on the actual total weight of the core W, an equation develops which for equality must have a decibel adjustment applied.

$$db_w + db' = K_4 + 6.67 \log_{10} FW + K_5 \log_{10} \frac{W}{W_0} \quad \ldots\ldots (15)$$

in which db′ = the decibel adjustment for weight,

F = weight equivalence factor.

Since Eq. (12) was in balance, as is Eq. (15), equals must have been added to each side, or,

$$db' = 6.67 \log_{10} F \quad \ldots\ldots (16)$$

From the definition of our mythical transformer, db′ must equal the correction for differences of induction had the weight been held constant. Therefore,

$$db' = db_B$$

$$6.67 \log_{10} F = 40 \log_{10} \frac{B}{B_0}$$

$$F = \left(\frac{B}{B_0}\right)^6 \quad \ldots\ldots (17)$$

It is now possible to make a very good approximation of the sound level produced by a transformer in which the tongue and yoke irons operate at different inductions, neither of which is likely to be equal to the reference induction. This is accomplished by weighting each mass of core material in accordance with its respective induction and adding to give the equivalent weight of core of a mythical transformer operating at reference density and producing the same sound level. This equation is

$$W_E = F_T \times W_T + F_Y \times W_Y \quad \ldots\ldots (18)$$

in which

W_E = weight of core of equivalent transformer operating at reference density, in percent of weight.

W_T = weight of tongue iron of real transformer operating at induction B_T, in percent of total weight.

W_Y = weight of yoke iron of real transformer operating at induction B_Y, in percent of total weight.

F_T = weight equivalence factor for induction B_T.

F_Y = weight equivalence factor for induction B_Y.

The frequency spectrum of this mythical transformer will not be exactly that of the real one, but the overall sound level as measured by a sound level meter is reliable.

All data producing the band B - B′ on Fig. 5 has been adjusted to reference density in the manner just described.

Measurements on identical transformer often extend over a large part of the band width of Fig. 5. This is probably caused by the relative perfection of workmanship and by variations in magnetostriction between heats of core steel.

In general, transformers with higher exciting currents, compared with otherwise identical transformers, produced higher sound levels. This is not wholly unexpected as exciting current is a measure of the quality

of the steel and the size of the gaps at the punching joints. It can be supposed then that wherever a gap exists, the adjacent lamination will possess finite freedom of longitudinal motion. Laminations bridging this gap will similarly be allowed freedom in a transverse direction, which allows the lamination to bend under magnetic influence.

Radiators by themselves are good sound conductors, and one would therefore expect little effect from them on the overall sound level. Tests, however, indicate a slight reduction. This can be explained when it is remembered that their presence increases the periphery of the sound radiating surface, and since the total sound energy generated by the core is fixed, the energy density at the periphery is reduced.

The reduction of the sound level of transformers is quite complicated. Economics is a major obstacle to sound reduction, because most methods of noise reduction involve increasing the cost of the transformer.

Appendix

All measurements for Fig. 5 were made in accordance with these standard recommendations[3] for test conditions:

1. Measurements shall be made in a space having an ambient sound level preferably 10, but not less than 7 db, lower than the sound level of the transformer and ambient combined. The ambient level shall be determined by at least 4 measurements immediately before and 4 measurements immediately after the apparatus is tested.

   The following corrections shall be applied:

Difference in db between ambient plus apparatus sound level and ambient sound level	7	8	9	10	Over 10
Correction in db to be applied to ambient plus apparatus sound level to obtain apparatus sound level	–1.0	–0.8	–0.6	–0.4	0

2. The transformer shall be so located that there is no acoustically reflecting surface, other than the floor or ground, within 10 feet of the transformer.
3. The transformer shall be energized at normal voltage and frequency, with no load.

   The measurement conditions are as follows:

1. Sound level shall be measured with an instrument that is in accordance with the ASA Tentative Standards for Sound Level Meters Z24.3. Response Curve A (for a 40 db sound level), shown in these standards, shall be used.
2. The average sound level is defined as the arithmetic mean of the sound level readings taken as specified in paragraphs 4 and 5 below.
3. The major sound producing surface is taken as the periphery over radiators, tubes, switching compartments, potheads, etc., but neglecting minor projections such as valves and thermometers.
4. For units less than 8 feet in overall height of tank, measurements shall be made at approximately half height. For units 8 feet and over in height, measurements shall be made at approximately ⅓ and ⅔ height.
5. All sound level measurements shall be made one foot from the major sound producing surface of the transformer; and approximately uniformly spaced around it. Measurement locations shall not be more than 3 feet apart and not less than 8 in number.

[3] See NEMA Recommended Practice TR6-40, Audio Sound Levels for Distribution and Power Transformers.

TABLE I

AUDIO SOUND LEVELS FOR DISTRIBUTION AND POWER TRANSFORMERS

DECIBEL LEVELS

*55 C Equivalent Kva	69 Kv and Below Insulation Class		92-115-138 Kv Insulation Class		161 Kv and Above Insulation Class	
	Without Fans	With Fans	Without Fans	With Fans	Without Fans	With Fans
0- 300	56	70	..	..	..	..
301- 500	58	70	..	..	..	..
501- 700	60	70	..	..	..	..
701- 1000	62	70	67	72	..	..
1001- 1500	63	70	68	73	..	..
1501- 2000	64	70	69	73	..	..
2001- 3000	65	71	70	74	72	76
3001- 4000	66	71	71	75	73	76
4001- 5000	67	72	72	76	74	77
5001- 6000	68	73	72	76	74	77
6001- 7500	69	73	73	76	75	78
7501-10000	70	74	73	76	75	78
10001-12500	71	75	74	77	76	79
12501-15000	72	76	75	78	77	80
15001-20000	74	77	76	79	78	81
20001-25000	75	78	77	80	79	82
25001-30000	76	79	78	81	80	83

* Applies to oil insulated self-cooled, oil insulated water-cooled, oil insulated forced-cooled, and to the oil insulated self-cooled rating of a combination self-cooled, forced-air-cooled transformer.

Transformers can be so designed that the average sound level will not exceed the decibels given in Table I when energized at normal voltage and frequency and at no load.

The value of decibels corresponding to the equivalent 55C kva ratings for any 50 or 60 cycle, single- or three-phase distribution or power transformer as defined by NEMA standards are given in the tabulation. These requirements do not apply to rectifier, railway or furnace transformers, or to transformers with mechanisms operating in the case of transformers with tap-changing under-load equipment or with switches operating in cases where the switch is integral with the transformer.

When guarantees are to be given for the sound level at 100 percent excitation and forced-air equipment in operation, use the values given in the columns headed "With Fans," corresponding to oil insulated self-cooled ratings.

ON FOLLOWING PAGES: Mighty motor armatures that dwarf Allis-Chalmers workmen will soon figure in the production of power for Victory. Largest, in the background, is for a steel blooming mill.

THE NINETEEN BASIC U. S. INVENTIONS
I. FOOD AND CLOTHING*

Are there simple, yet important things left to invent? All 19 basic inventions now look simple, but when each was devised everyone wondered if such a gadget could have practical value.

Miles Henninger

PATENT ATTORNEY • ALLIS-CHALMERS MANUFACTURING COMPANY

Inventions are the result of intelligent observation and painstaking effort continued until a desired result is reached, and are not necessarily the result of a "flash of genius" as our present Supreme Court has ruled. Consideration of even the basic inventions which are of the greatest use to man, and on which large industries are based, shows that invention is an evolutionary process.

The basic inventive results are often so embryonic or crude that the so-called practical man can see little use in them. When Gladstone saw Faraday's transformation of mechanical energy into electricity by induction, he asked, "Will this ever be of use?"

Faraday replied, "Some day you will collect taxes from it." Taxes collected from industries based on inventions are insignificant compared to the labor and time saved in producing more food, clothing, and shelter for greater populations, resulting in a constant decrease in fear, pain, and want.

The study and time required for creating an invention has to be compensated to encourage more and greater efforts, and such compensation should be measured by the actual value of the invention to the public. So far, man has devised no better yardstick for measuring the public good resulting from invention than "securing for limited times . . . the exclusive rights to their . . . discoveries." This is the grant in a patent under which, in practical usage, people other than the inventor are excluded by the aid of law from practicing the invention for a definite period after issuance of the patent.

Whether or not the United States patent system would have proved to be a stimulus to ingenuity under the conditions prevailing in any other country is questionable, but in this country the system has resulted in crediting Americans with 75% of all the world famous inventions. The United States patent system certainly has been well adapted to inspire maximum individual mental and physical efforts in the United States system of individual enterprise.

Uninformed critics to the contrary, the United States patent system has provided and still provides a path any one may travel to modest fame and improved economic circumstances. However, merely getting a patent in the belief that the world will beat a highway to your door is not enough. Nor is the mentally lazy or economically ignorant person justified in the belief that tremendous financial or manufacturing resources are necessary to make a commercial success of a patented article. Consideration of the 19 most famous American inventions shows that an inventive idea must be combined with knowledge of the patent system, of economic laws, and perseverance to make even the best of inventions available to the public, as well as a source of profit.

The busts of Fulton, Howe, Morse, and Whitney in the Hall of Fame will always keep alive the memory of their work. But so far there is no public memorial to the other 15 inventors for their contributions to modern convenience and safety. The neglected 15 have done much to relieve drudgery, to provide better living conditions, and to add to the world's true wealth.

The life and training of the 19 most famous inventors shows that inventive genius is not confined to any one group or to any one particular kind of training. None of the inventors was insensible to the fame and financial rewards possible should his invention fill a public need or desire; and all their inventions were motivated by a belief that some particular problem could be successfully solved. Often the steps in making an invention were separated by periods of hard work and disappointment, but the work continued until the idea was reduced to a practical form. The financial returns to inventors in some cases were nothing or negligible and in other cases were very substantial. However, in every case the invention formed the basis for an industry which has provided the public with a more abundant or cheaper article, or a product not previously available. Every one of these industries has made a living for numerous workers.

The basic essentials of food and clothing are more available, at least in the United States, largely because of Whitney's cotton gin, McCormick's harvester, and Howe's sewing machine.

* The first of four articles considering the 19 most famous American inventions to illustrate what must be combined with an inventive idea to make it useful to the public and a source of profit to the inventor and exploiter.

Whitney's Cotton Gin 1794

Eli Whitney was the son (1765) of a farmer at Westboro, Mass., and early in life chose to utilize his aptitude for tinkering with mechanical devices in his father's repair shop in preference to farm work. During the Revolutionary War, Whitney hand-forged cutlery, nails, and ladies' hat pins for income. His father was prosperous enough to give him a higher education, and Eli graduated in 1792 in arts, then the only course available, from Yale and accepted a tutoring position with a plantation owner at Savannah, Ga., for 100 dollars per year and board. When Whitney reached Savannah, his prospective employer refused to pay the high salary agreed upon, so Whitney went to visit Mrs. Nathanael Greene, a family acquaintance and widow of the Revolutionary War general. On the Greene plantation Whitney amused himself by making mechanical toys for the Greene children and gadgets such as an improved embroidery frame for Mrs. Greene.

At that time cotton was only one of the plantation crops. The agricultural problems of growing cotton were solved; but planters had only slow hand-picking for eliminating the seeds, and the problem of removing seeds from cotton was a favorite topic of conversation. Mrs. Greene facetiously referred her fellow planters to Whitney for a solution of the problem. The conversation proved to be a challenge to Whitney, so he set about to meet it. It was commonly conceded that a successful cotton seed removing device would be very profitable, and Whitney needed the money.

Up to that time only four pounds of cotton could be hand-cleaned by one worker in a day, and the total United States crop in 1791 was only about 200,000 pounds, compared to present-day 15,000,000 bales. In the West Indies, a pair of rollers had been adapted to remove the large, loosely held, black seeds from the long-fiber lowland cotton. But the domestic short-fiber cotton was upland-grown and had small, tightly held, green seeds which could not be rolled out, but had to be combed out.

By the late winter of 1793 Whitney had devised a large-scale combing device with a hopper having side bars, spaced to allow cotton fibers to pass between the bars, a rotating cylinder with saw or wire teeth passing between the bars to pull out the fiber; and a rotating brush to remove the cotton fiber from the cylinder teeth. Whitney had trouble building the first model because he could find no iron plates or sheets suitable for making the saw tooth cylinder, so he had to draw down the only available wire to a size to suit his purposes. The device produced the desired results, and a cotton gin was born which truly made cotton king of plantation crops. Whitney received a patent on the cotton gin (Fig. 1) on March 14, 1794, and immediately accepted the financial aid of Miller (Mrs. Greene's plantation superintendent) to manufacture cotton gins.

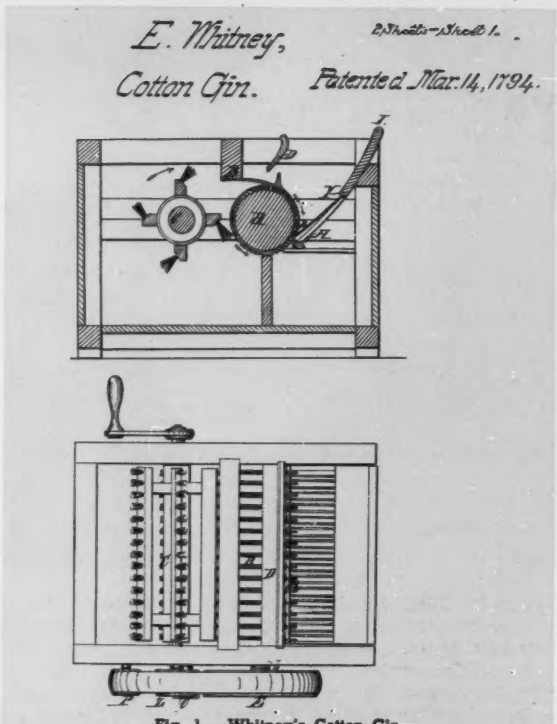

Fig. 1 — Whitney's Cotton Gin

The gin was quickly and widely publicized both by Whitney and his friends before any facilities were available for supplying the resulting market, and this publicity proved premature. Whitney and Miller, in the face of the immediate and large public demand and without any manufacturing facilities, proposed to manufacture and lease cotton gins at the exorbitant rate of one-third of all of the cotton ginned, so their troubles began. Whitney's first model was stolen, and soon every competent carpenter-blacksmith was making gins. Whitney and Miller wasted considerable effort in trying to collect their proposed royalty, and finally offered to license any gin for $200. Even this fee was too high for an article obtainable for half that price or less. As a last effort to obtain a return on the patent itself, licenses to use gins were sold to several cotton-growing states for a total royalty of approximately $90,000. However, even that royalty was consumed in litigation with Hodgkin Holmes, who patented and marketed a gin with a wire tooth cylinder.

Whitney and Miller also tried to get some profit by manufacturing gins. A factory built at New Haven, Conn., burned with all its complete gins and parts before a serious attempt could be made to supply the market. By the time a second factory was built only a relatively small market remained. The second factory was, however, profitable because Whitney received a War Department contract for 100,000 muskets and he filled the contract by developing special power-driven machine tools for producing indefinite numbers of individual and interchangeable parts, thus originating the mass production system.

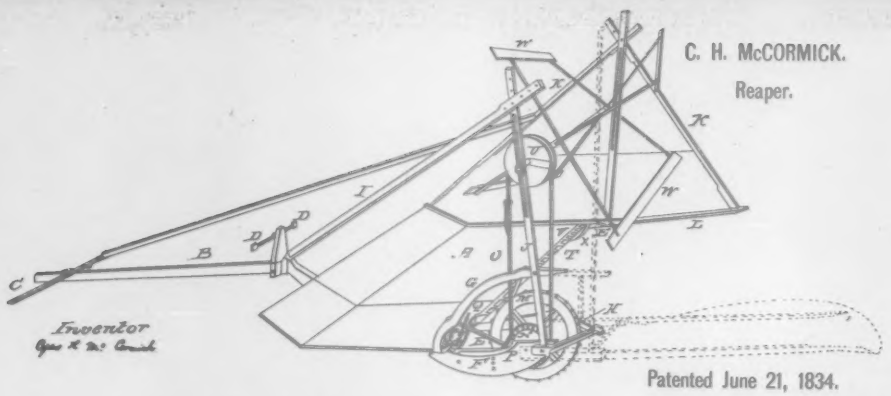

Fig. 2 — McCormick's Reaper

McCormick's Harvester 1834

Cyrus H. McCormick (born 1809 in Midvale, Va.) invented the harvester after his father had abandoned several attempts to perfect the implement. The father, Robert McCormick, owned an 1800 acre farm and operated a sawmill, a grist mill, and a blacksmith shop, which acquainted Cyrus with farm problems and gave him some mechanical experience to supplement a grade school education. Robert McCormick began his work in 1816 and by 1831 he had evolved a reaper with a reel pressing the grain against rotary knives revolving past the edges of stationary knives. The grain had to be raked off a platform by hand. Tests proved that the revolving knife cutter choked so often that it was useless.

Meanwhile with the stimulus of a prize offered by the Royal Agricultural Society, Henry Ogle, an English schoolmaster, in 1822 patented a reaper with a cutting knife reciprocating behind stationary fingers. Rev. Patrick Bell in Dundee, Scotland, had by 1828 produced a reaper which had the reel, an elevator to discharge grain in a swath at one side of the machine and a cutter bar made up of twelve pairs of shears, each having one of the blades stationary and the other pivoted. The Bell reaper was also unsatisfactory because the shear cutters choked. English farmhands destroyed Bell's machine and beat the inventor. Obed Hussey, a sailor of Nantucket, Mass., invented a reaper (patented December 31, 1833) with saw toothed blades reciprocating between upper and lower wire guards. He manufactured the machine for seven years, but he did not make improvements and so lost the race to McCormick.

Cyrus McCormick, with his father's permission, began work on a harvester in 1832, and, after the bankruptcy of his foundry business, he made two notable changes in the machine. Cyrus changed the cutter to a bar with sawlike cutting teeth reciprocating in wire guards and added a divider separating the grain to be cut from the grain to be left standing (15 L. E. 930). After some tests followed by more changes, McCormick was certain that a practical harvester had been produced so the machine was patented on June 21, 1834 (Fig. 2).

However, the fields of the eastern states were too hilly and the farms were too small to justify the $50 price of the harvester. From 1841 to 1844 only 88 machines had been sold, and seven of these went to the Middle West. Cyrus went out to the Middle West to straighten out delivery of machines and here he saw the level prairies with their grain fields. He recognized the need for a harvester here and selected Chicago as a factory site because of its railroad facilities. With neither credit nor money, McCormick persuaded William Ogden (then mayor of Chicago) to advance $25,000 for a half interest in the patent. Five hundred reapers were sold in 1848, 1500 in the following year. McCormick then repurchased Ogden's half interest for $50,000 and continued the business in his own behalf, later changing it to the International Harvester Co.

McCormick received the Grand Council medal at the London World's Fair in 1851 because his machine was worth "the whole cost of the exposition" to the people of England. He was elected to the French Academy of Sciences for "having done more for the cause of agriculture than any living man." After his death in 1884, a probate of his estate showed a fortune of $10,000,000.

McCormick was thoroughly conversant with the problem of harvesting grain. He manufactured enough reapers to supply the market at a price which left a margin of profit over hand labor and he located his factory near marketing facilities.

Howe's Sewing Machine 1846

The invention of the sewing machine is a story of struggle against difficulties solved only by the exploitation of the invention by a person other than the inventor. Elias Howe was born in 1819 at Spencer, Mass., on a farm which, with a grist mill, a sawmill, and shingle machine, provided only a very meager living, and Howe was apprenticed when eleven years old to a neighbor. Howe was so lame (probably infantile paralysis) that the physical labor of that time

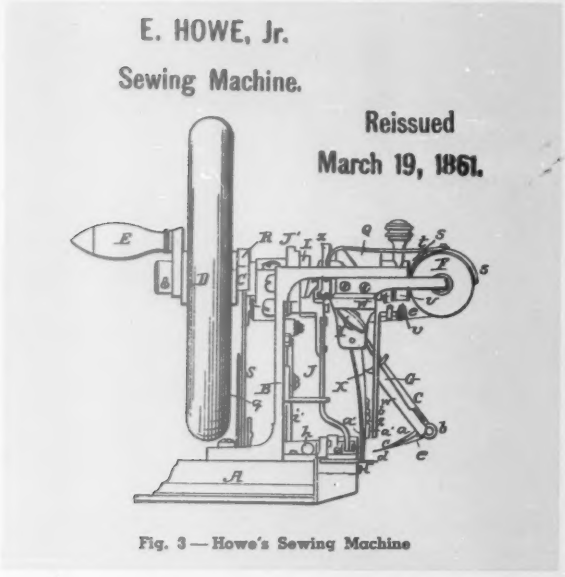

Fig. 3 — Howe's Sewing Machine

was almost impossible for him, so at sixteen he sought easier work in the Lowell mills making textile machinery. The mills closed, and he drifted to Cambridge where he worked in Davis' shop for repairing watches, surveying, and other technical instruments. A conversation between Davis and a customer started Howe thinking about sewing machines.

Howe's efforts were preceded by those of Thomas Saint of London, who obtained an English patent (1,764, July 17, 1790) on a sewing machine. Napoleon's army was largely uniformed by means of sewing machines made in France by Bartholomey Thimmonier in 1830. Then tailors, with the aid of others, twice burned all of his machines and his factories and threatened him with injury. He came to the U. S. A. in 1850, but was unable to begin the manufacture of sewing machines. Walter Hunt of New York also built a model sewing machine in 1832, but neither the Saint, Thimmonier, nor Hunt machines were entirely practical. They were never marketed nor described in print so there was no information generally available on these machines.[1] Howe's machine was therefore not an evolution from the work of others, but the result of his own ideas, spurred by the necessity for easing the hard physical labor required to support his wife and three children on $9.00 per week.

The first step toward a successful sewing machine was the conception that two eye-pointed grooved needles might be made to form interlocking loops. Step two was the substitution of a shuttle for one needle and invention of the mechanism for reciprocating the needle and the shuttle. Step three was the instituting of a mechanism for maintaining tension on the threads. Then the cloth had to be held taut on a pin baster plate and passed before the needle. At this time Howe built a machine with the aid of George Fisher who bought a half interest in the invention for $500, room and board for Howe and his family, and an attic for Howe's workshop. The two men tried to sell the machines by demonstrations and by contests against the fastest seamstresses of the time but found no purchasers. Fisher became discouraged and withdrew from the venture.

Howe borrowed money and sent his brother to London, where he sold one machine to William Thomas, a manufacturer of corsets, carpet bags, and shoes, for $1500. The sale included all English rights to the invention at a royalty of $15.00 per machine. Thomas offered Howe $15.00 per week to come to London and adjust his sewing machine to the making of Thomas' products. After Howe had done the required work, he was discharged, and no royalties were ever paid by Thomas.

Further efforts to sell machines in England resulted in the sale of one for $25.00. For days Howe lived on as little as 25 cents' worth of beans cooked in his room. He pawned his clothes, his first machine, and his Letters Patent (patent 4750, September 10, 1846, and reissued 1154, March 19, 1861) (Fig. 3), and he finally returned to New York in the steerage as a cook with 50 cents remaining after four years of work and privation. Before he could earn enough money to go back to Cambridge, his wife died of malnutrition and tuberculosis, and Howe had to borrow the clothes in which he appeared at her funeral.

Howe persisted in trying to exploit his sewing machine and in so doing attracted the attention of Isaac M. Singer, who realized that public acceptance of the sewing machine was delayed because the Howe machine could sew only a straight seam, cost from $200 to $300, and frequently broke down. In eleven days of day and night work Singer and his assistants added the overhanding needle arm, the presser foot near the needle and the double acting threadle. These improvements permitted the machine to sew on curves, removed the pin baster plate which was difficult to handle and eliminated the need for hand cranking the machine.

Singer knew advertising. He used posters, pamphlets, newspapers, and any other available printed material. He employed shows with bands and beautiful young demonstrators in lavishly decorated show rooms. He held contests and gave prizes. He organized a localized selling organization, and the Singer Sewing Machine Co. is based on Isaac Singer's work beginning about 1850.

However, Singer paid no attention to Howe and gave him no credit. Howe again sold a half interest in his patent to George W. Bliss for enough money to prosecute infringement of his patent by Singer and others. During the litigation Bliss' heirs resold to Howe the half interest at a low price because of the uncertainty of a favorable court decision. After four years of litigation, the Supreme Court held "There is no evidence . . . that leaves the shadow of a doubt that, for all benefits conferred on the public by the invention of the sewing machine, the public is indebted to Mr. Howe."

Thereafter, Howe for a long time received a royalty of $25.00 on all sewing machines made in the U. S. A. Howe's patent was extended by Congress in 1860 for seven years. In his petition for a second extension he acknowledged having received $1,185,000, but he considered his invention worth $150,000,000. Congress, however, considered that Howe's 20 years of struggle and starvation had been sufficiently repaid.

(To be continued in next issue)

[1] 1921 Journal of the Patent Office Society, p. 433.

FINDING HIDDEN KILOWATTS

Service factors built into electrical machinery in pre-war days now mean more horsepower on production lines. That a machine will outlive the war can be insured by checking a few simple factors.

Fraser Jeffrey

ASSISTANT TO CHIEF ELECTRICAL ENGINEER • ALLIS-CHALMERS MANUFACTURING COMPANY

Today engineers think about how to get more capacity not only from present electrical equipment, but also from new equipment that will be built and soon installed. Whatever additional capacity can be safely squeezed out of electrical equipment will result in actual savings in critical materials.

Many good engineers have already studied these possibilities of greater capacity both from the manufacturing standpoint as well as from the application and operating standpoint. The War Production Board, in December, 1942, issued its General Conservation Order L-221, restricting ratings of motors and generators with respect to determined loads. Committee reports dealing with restriction of ratings and loading of equipment were presented at the AIEE Mid-Winter Convention in New York in January, 1943.

There are four general factors that have to be considered when it is intended to operate electrical equipment above its normal rating:

1. Temperature standards to which the machine was built.
2. Temperature limitations and possibilities.
3. Differential expansion, contraction of windings.
4. Insulation life.

The approach to increased capacity may be compared somewhat to the life of a man. Life insurance actuary figures allocate, on an average basis, the number of years which any given man can be expected to live. Some men may live considerably longer, while others may drop out before the time allotted to their life span. If a man who has lived a normal life is suddenly confronted by an emergency condition which necessitates accelerating the pace of his living and working, his life span, neglecting hereditary trends, will quite likely be decreased, probably in proportion to the rate at which he accelerates his living and work.

The same thing is true in electrical apparatus, where, just as with the man under normal conditions, a certain length of life is expected. The life of the machinery will also be shortened in a definite ratio to the amount of the extra loading imposed.

Series limitations

There is one great difference between the man and the electrical equipment that cannot be overlooked. A man can accelerate his working capacity to any limit which he can stand, but electrical machinery is limited in working capacity by the limits of all the interconnected electrical equipment and all other power equipment associated with it.

For example, a generator with considerable overload capacity may not be able to utilize this excess capacity because of the prime mover. A diesel engine, for instance, unless specially designed otherwise, can usually handle only a 10 to 15% overload, and even then with smoky exhaust. On the other hand, a steam turbine driving a generator built for a given KVA load at 80% power factor is usually capable of running the generator at full kw, unity power factor, or the equivalent of 25% overload.

Switchgear usually is maximum rated and, therefore, cannot carry overloads unless the original installation had greater capacity than needed at that time. Many other items of associated equipment must all be given consideration when increased capacity from present equipment is contemplated.

Temperature standards

Limiting insulation temperatures and temperature rises have been established by the AIEE and the American Standards Association. These standards limit Class "A" insulation to 105 C, and Class "B" insulation to 130 C maximum (Fig. 1). The total limiting temperatures are arrived at by adding the ambient, rise, and hot spot temperatures.

AT RIGHT: A 70-ton hitch, this crane load is the generator half of the low-pressure exhaust end and cover for one of the largest steam turbine units under construction in America.

Gentlemen:

Yes, I want to see your new sound movie, "The Magic of Steam," which describes steam turbine operation. Please send me 1 print for showing on_____ or _____ (to supply the demand for this film, alternative dates are requested).

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Method	CLASS "A" INSULATION					CLASS "B" INSULATION				
	Safe Lifting Observable Temp. A.S.A.	Rise A.S.A.	Ambient A.S.A.	Hot Spot AIEE	Total Limiting Temp.	Safe Lifting Observable Temp. A.S.A.	Rise A.S.A.	Ambient A.S.A.	Hot Spot AIEE	Total Limiting Temp.
Thermometer	90C	50C	40C	15C	105C	110C	70C	40C	20C	130C
Resistance	100C	60C	40C	5C	105C	120C	80C	40C	10C	130C
Embedded Det.	100C	60C	40C	5C	105C	120C	80C	40C	10C	130C

Fig. 1 — Standard limiting observable temperatures and temperature rises.

INDUCTION MOTORS												
Method	Usual Temperature Rises Specified				Possible Increased Temp. Rises that Might Be Allowable				Possible Increased Total Limiting Temperatures			
	Class "A" Insulation		Class "B" Insulation		Class "A" Insulation		Class "B" Insulation		Class "A" Insulation		Class "B" Insulation	
	Stator	Rotor	Stator	Rotor	Stator	Rotor	Stator	Rotor	Stator	Rotor	Stator	Rotor
Thermometer	40C	40C	50C	50C	50C	50C	60C	60C	105C	105C	120C	120C
Resistance	50C	50C	60C	60C	60C	60C	70C	70C	105C	105C	120C	120C
Embedded Detector	50C	50C	60C	60C	60C	60C	70C	70C	105C	105C	120C	120C

Fig. 2 — Possibilities for securing increased capacity from induction motors above 200 hp.

The reason for this procedure is quite easily understood. If the temperature could actually be measured on the copper in the coils in the central and least ventilated part of the machine, this copper or hot spot temperature ordinarily would be about 15 C hotter than anything that could be measured by the thermometer method. It would be about 5 C hotter than the temperature that would be recorded by the resistance method or with embedded detector. Therefore, the standards as set up make allowances to compensate for these differences in methods of temperature measurements.

In the thermometer method, the instruments are set on the ends of the stator coils, in the core ducts, and on the core itself. This method gives the greatest difference between observed temperature and the actual hot spot temperature.

In the embedded detector method, resistance coils or thermocouples are located between the lower and upper stator coil sides in the middle of the stator core, and the readings more nearly approach the actual hot spot temperatures. This method, however, is practical only in large equipment.

The resistance method determines the temperature rise from the increase in resistance of coils as they get hot. This method, of course, gives average temperatures, but more nearly approaches the actual hot spot temperature than do temperatures indicated by thermometers.

More temperature rise?

Most induction motors have been of liberal design and are capable of carrying an appreciable increase in load over their rating (Fig. 2). By increasing the rating of the motors to allow a nominal temperature rise of 50 C instead of the usual 40 C with Class "A" insulation, and 60 C instead of 50 C for Class "B" insulation, the maximum allowable temperatures for these classes of insulation will still not be exceeded.

The War Production Board Limitation Order L-221 and the AIEE committee report on "Selection of Electric Motors" issued in January, 1943, give the maximum ratio of actual load to selected motor rating as 1.25 in most cases. It is evident that the usual service factor of 1.15 has been exceeded. For Class "A" insulation the "Possible Increased Total Limiting Temperatures" standards might be exceeded by 10 C, i.e., 115 C instead of 105 C; but the new temperatures are exactly the same as the standards for Class "B" insulation, namely 130 C. As will be shown later, the life expectancy of the insulation under such conditions will be considerably reduced.

The same relative increases in temperature ratings are applied to direct-current and all synchronous machines except turbo-generators, which are considered as a special case.

There is considerable variation of temperatures because of different structural features of different machines. Therefore, it is always well, when considering possible changes in loading, to be guided by the nameplate ratings on the individual machines in question, or better still, by actual test or load temperatures.

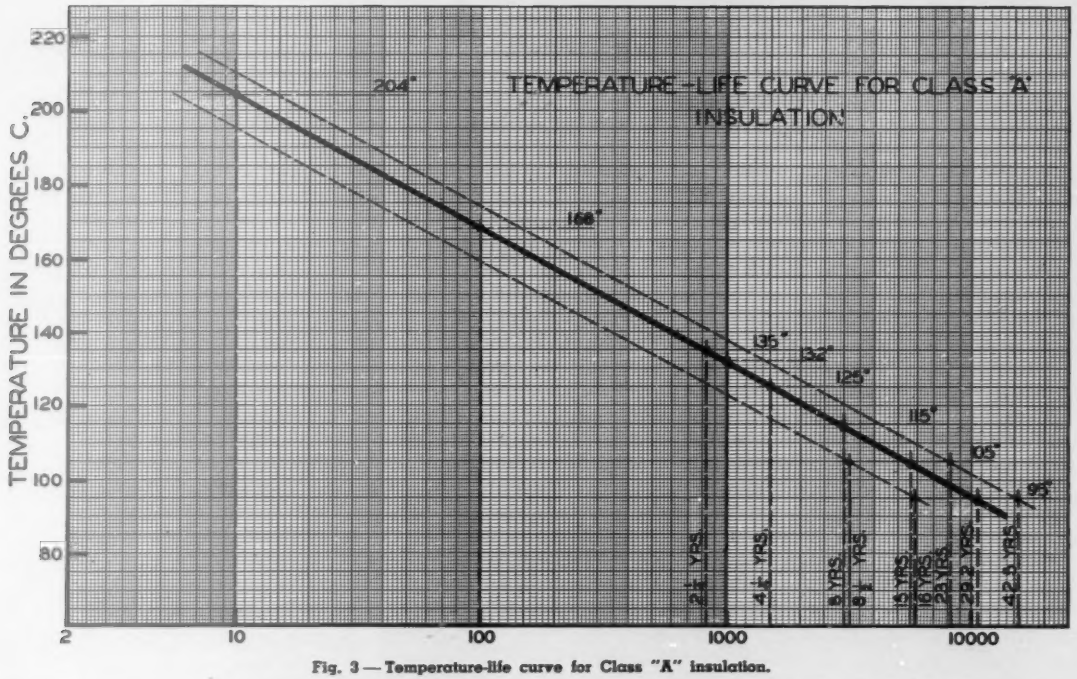


Fig. 3 — Temperature-life curve for Class "A" insulation.

Differential expansion and contraction of windings

Machines that are not operating on steady loads, such as generators used only for a few hours daily or generators operating continuously on highly fluctuating loads, should not be allowed to run at as high a temperature as machines that are run for long periods of time with steady loads and relatively few shutdowns.

The wear and tear on insulation caused by the differential expansion and contraction between the copper and the iron becomes more pronounced at higher loads and higher temperatures, and more severe with sudden changes in load. The effect of differential expansion also is greater in long machines and for this reason applies particularly to high speed equipment of the turbo-generator class.

Differential expansion causes slippage of insulation on the coils, or slippage between the coil insulation and the core laminations. If the temperature changes are great enough and occur often enough, they finally result in insulation failure. These conditions apply particularly to long core machines, but they show that the effects of temperature on the life of insulation are not always caused by chemical aging.

Life of class "A" insulation

A temperature-life curve for Class "A" insulation is shown in Fig. 3. The curve is represented as a band which, for instance, shows a life expectancy at 105 C varying from 8½ to 23 years. The solid line in the center of the band, showing a life of 15 years at 105 C, provides a definite straight line for making comparisons. It will be remembered that 105 C is the total safe limiting temperature for Class "A" insulation set up as a standard by the AIEE.

The solid line life curve shows that if a steady temperature of 105 C is maintained for 15 years, Class "A" insulation will theoretically reach the end of its useful life and will then fail under mechanical or electrical shock. On the other hand, if a steady temperature of 95 C can be maintained for Class "A" insulation, the theoretical life will be 29.2 years.

Although these values are referred to as theoretical, the insulation life curves were established from accumulated laboratory and field experience data on life of Class "A" insulation in various temperatures. These curves permit making reasonable estimates of the life span of this type of insulation.

Class "B" insulation life

No similar life curve data are available for Class "B" materials. At the present time it is assumed that the life of a winding with Class "B" insulation is greater for Class "A" temperature rises than for Class "B" temperature rises. Class "B" materials do not appreciably deteriorate from the high temperatures, but the bonding materials that are used in Class "B" insulation are seriously effected. The life expectancy of an

insulation is considerably shortened by the deterioration of the bonding material.

The relation between the life expectancy of insulation, as indicated by laboratory and field tests, and the life of the insulation in any given machine is an estimate, so the use of this information must be tempered by sound judgment based on operating experience.

General considerations

Very few machines operate continuously at their maximum rated loads so that the life expectancy of the insulation may be extended because of operation at lower temperatures.

It will be noticed that in general the life of Class "A" insulation is halved approximately for each 10 C increase of temperature. For instance, at 115 C the life of the insulation has been reduced to 8 years; at 125 C to 4¼ years, at 135 C to 2¼ years; until at the temperature of 168 C the life is reduced to 100 days; and at 204 C it would be reduced to 10 days.

Thermal time constant

Every piece of electrical equipment has what is called a "thermal time temperature constant" which indicates the rate at which the machine's temperature will rise with respect to time.

This constant is established from the initial and ultimate temperature rise obtained from the curve (Fig. 4) of time versus temperature. A tangent to the curve (tangent at the origin) intersects the ultimate rise at a point called the "thermal time constant." These time-temperature curves are interesting in that at 50% of the ultimate rise the time is always 69.3%

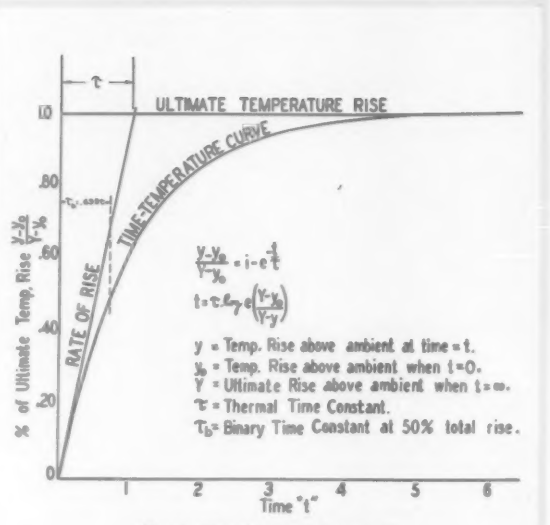


Fig. 4—Time-temperature curve.

of the time constant. Furthermore, a tangent to the curve at any point intersects the ultimate rise at a point one time constant farther to the right than the point of tangency to the curve.

Therefore, if the thermal time constant of a machine is known from actual test, and the initial heating and temperature rise during any single condition of loading is known, then it is possible to calculate the temperature rise under any other load condition, whether it is for continuous loading or short time loading.

The equation for the curve as well as the equation for the time "t" are also shown in Fig. 4. Different machines naturally have different time constants, and usually the larger the machine the greater the time constant.

The results of super-imposed loads by actual tests on a 2500 hp, 3600 rpm, squirrel cage induction motor which has a time constant of 15 minutes are shown in Fig. 5. If the time constant had been known and the constant temperature at say 2000 hp or any other load had also been known, it would have been possible to calculate within reasonable limits the temperatures at the other two loads, rather than having to make actual heat runs.

Thermal time constants and temperature rises from similar equipment can often be used in calculating temperature rises of new equipment. Design engineers make use of these factors for predicting temperatures for all kinds of different loadings.

Temperature has been rather fully discussed because it greatly influences insulation life. If consideration is being given to overloading electrical machines, it is necessary to have a very good idea of what temperatures will actually exist under overload before any close estimate can be made of the life expectancy for that piece of equipment.

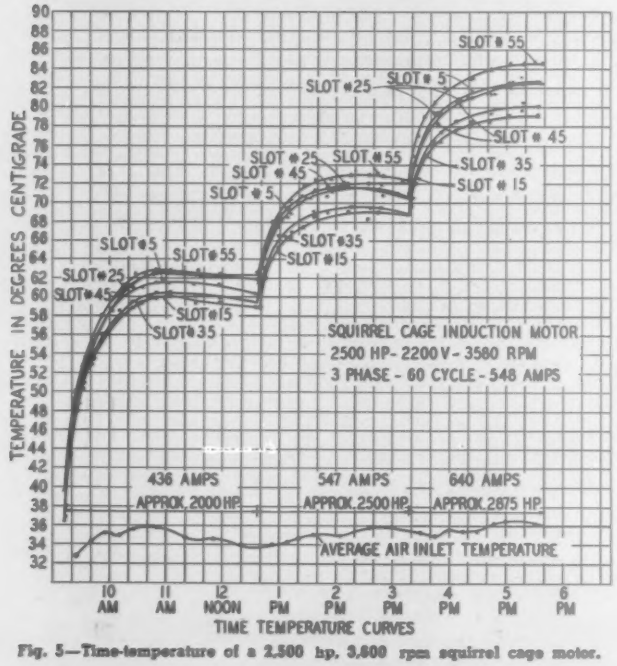


Fig. 5—Time-temperature of a 2,500 hp, 3,600 rpm squirrel cage motor.

CONTROLLED SPEED WITH A-C MOTORS

No direct-current power? D-c motors are ideal for variable speed output, but a compromise can produce the desired results economically too. Here are the ways in which alternating-current motors can supply variable speed power.

E. H. Fredrick and H. A. Petersen

MOTOR AND GENERATOR DIVISION • ALLIS-CHALMERS MANUFACTURING COMPANY

Widespread use of alternating current motors has introduced the problem of how to get the fine speed control formerly available with d-c motors. In many applications adjustable speed is advantageous even if not absolutely necessary. The direct current motor is unequaled for variable speed service, but many plants, especially the smaller ones, do not have direct current and, without expensive conversion equipment, these plants must rely on a-c motors for variable speed drive.

The characteristics of the motor and drive, the characteristics of the load, and relative costs are involved in the selection of a variable speed drive. Only general industrial service will be considered since heavy duty drives, such as those for metal rolling, require special consideration.

Advantages of variable speed drives

Sometimes control of speed helps improve the quality of the finished product. Rotary kilns, such as those used in chemical roasting operations or in the burning of lime or cement, are usually dependent on adjustable speed for control of the process. Other drives, such as winding reels, operate at a constantly varying speed because the rpm of the drive must decrease as the reel builds up to maintain a constant linear winding speed.

Operation at reduced speed is often accompanied by a reduction in maintenance and operating costs of equipment. For example, erosion of fan blades handling abrasive-laden air varies approximately as the cube of the speed of the air stream. This reduced maintenance may be appreciable enough to justify the cost of the variable speed equipment.

Requirements of a variable speed drive

The most important requirement of a variable speed drive is dependability, so it must be built ruggedly and simply to eliminate the possibility of failure of any of its parts.

A well designed drive must be sensitive to control. For example, in a blower drive it may be necessary that a very slight change in the air pressure causes readjustment of speed. The control should be as simple, yet it must perform the required functions.

Besides the range of speed, the number of speed points must also be considered. For instance, a multi-speed squirrel-cage motor will run only at any of two, three, or four operating speeds. Where close control of speed is not important, this limitation is not serious.

Efficiency and stability of operation must also be weighed. On fluctuating loads or on intermittent duty, the efficiency of a drive is not as important as it is in drives that run continuously at full or reduced speeds. The relative efficiencies of several variable speed drives are shown in Fig. 1. The curve for the d-c motor is shown for comparison. The efficiency of a variable pitch "V"-belt drive is comparable to that of the d-c motor.

Stability is more or less a function of load characteristics. Some loads are inherently stable and it is easy to change the speed. Other machines are very critical or sensitive to speed changes. The loading of these machines must be carefully analyzed before a selection of a drive can be made.

The speed of response is affected by the inertia of the load. Where the WR^2 of the load is high, it is necessary to check to see if the drive and its control will give the desired performance without excess complications.

Types of variable speed drives

Many variable and multi-speed drives have been developed, each with its own characteristics and each developed for a definite type of service. The following are common drives:

1. Mechanical Speed Changers
   a. Variable pitch V-belt
   b. Magnetic coupling
   c. Hydraulic coupling
2. Induction Motors
   a. Wound rotor motor
   b. Multi-speed motor

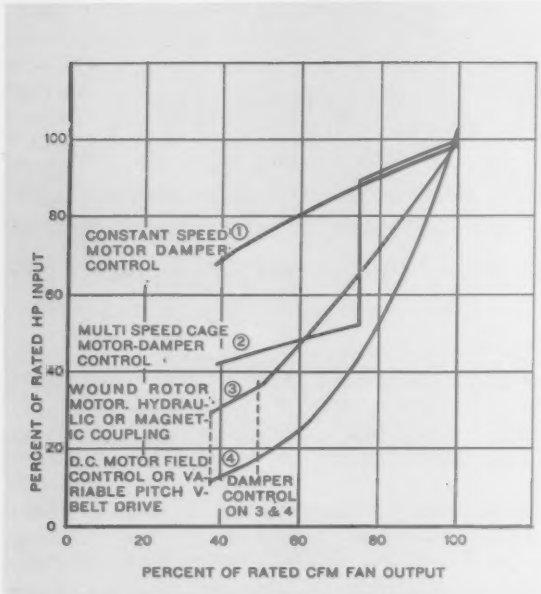


Fig. 1—Performance curves of various drives on a forced draft fan with fixed ducts.

In addition to these alternating-current variable-speed drives there are several other schemes, usually for large drives, for providing variable speed. The application of these drives, such as the Kraemer system, Scherbius system, Rossman drive, or dual speed synchronous motor, is very limited.

Variable pitch V-belt drives

The variable pitch V-belt drive, although usually limited in size to less than 100 hp, offers an excellent means of speed adjustment. Its principal advantage is that the output speed is independent of load, which gives the variable pitch V-belt drive a speed characteristic very similar to that of a shunt-wound d-c motor. For this reason variable pitch V-belt drives are used extensively on machine tools where a constant speed characteristic is very desirable.

On these speed changers the ratio can be changed with a screw adjustment which permits stepless settings of almost micrometric accuracy. Ordinarily a variable pitch V-belt drive can give speed ranges up to five to one, which is enough range for most applications.

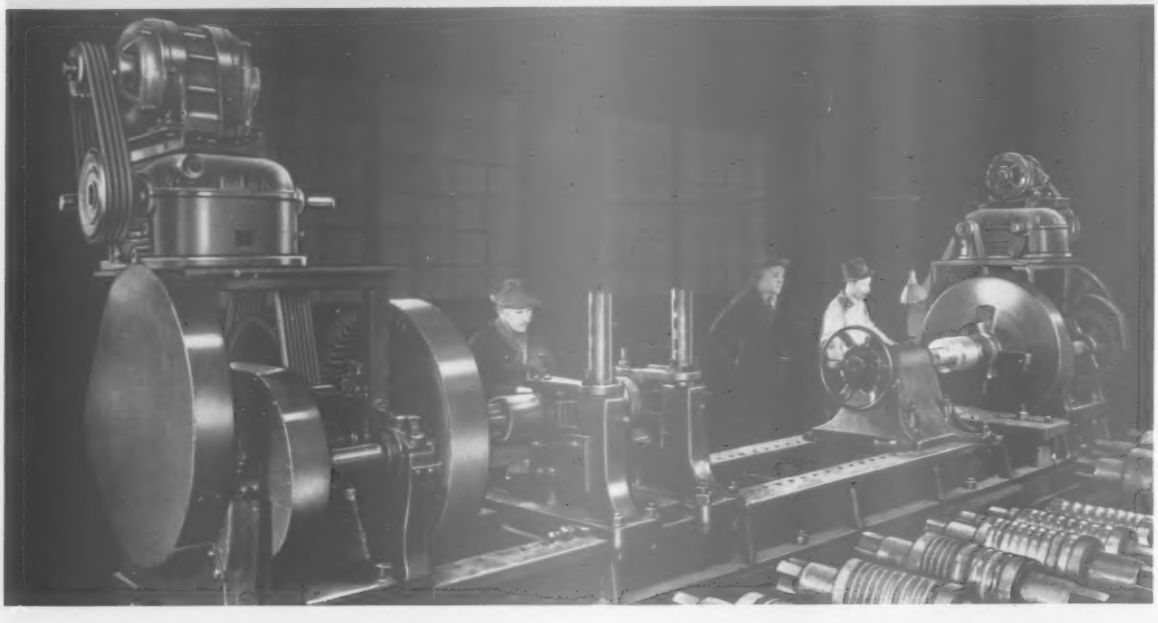
The variable pitch V-belt drive compares favorably in efficiency with any other type of variable speed drive. Under ideal conditions, the actual overall efficiency may be well over 90% for the whole speed range.

A variable pitch V-belt drive can usually be installed very easily on existing machines. On new installations a variable pitch drive usually requires less space than other possible drives. A variable pitch speed changer applied to a lathe is shown in Fig. 2.

Magnetic couplings

The simplest magnetic coupling is an eddy current clutch, in which a free disk follows the rotation of a magnetic field by action of currents induced in the disc.

Fig. 2 — A variable pitch speed changer applied to this lathe requires no additional space of any value.



A commercial magnetic coupling is analogous to a polyphase squirrel-cage motor. The excited or primary member is rotated by the driving motor. This rotation causes current to be induced in the secondary as in a squirrel-cage motor, and a torque reaction starts the secondary following the rotating primary.

The driven member of the coupling is usually a cylinder in which damper rods are embedded to localize the induced currents and provide an electrical path for them. Sometimes the secondary member is a solid casting with projections to serve as paths for the eddy currents.

The torque, and consequently the slip between the driven and driving members, is very readily controlled, within limits, by the amount of excitation in the field coils. On large units the slip at top speed may be as low as one percent, but commercial units usually have a minimum slip of two to three and one-half percent at full speed and full load. At reduced speeds the losses in the coupling are practically the same as those of a wound rotor motor. With a constant torque load the losses will be proportional to the slip.

In most fan or centrifugal pump drives the horsepower input varies with the cube of the speed. The losses at reduced speed are much lower than in a constant torque drive, so magnetic couplings are very well adapted for such pumps and fans. When operating at greatly reduced speeds on a variable torque load, the magnetic coupling tends to be unstable. This objection, however, can usually be overcome by means of suitable automatic control.

The wound rotor motor utilizes a secondary resistor to dissipate the heat generated by the losses external to the motor proper. On the other hand, in the magnetic coupling these losses are all liberated inside the unit and dissipated in the unit itself. In small units air cooling similar to that employed on squirrel-cage motors is common. Recently water cooling of large capacity units has made it possible to reduce their size.

A magnetic coupling driving an induced draft fan is shown in Fig. 3. The direct-connected exciter for exciting the coupling is mounted on the induction motor shaft.

Hydraulic couplings

Hydraulic couplings differ from magnetic couplings in that a fluid is used in connection with transmitting torque from an impeller to a runner. Automobile manufacturers have adopted hydraulic couplings on a limited scale, primarily for clutching.

The hydraulic coupling is fundamentally an impulse turbine. One set of driving vanes or blades, mounted axially to the shaft, causes a flow of oil to impinge on a second set of blades mounted on the driven member. This flow of oil effectively transmits the torque from the driving to the driven member. The amount of torque transmitted depends on the quantity of oil recirculated, and very fine control can be had merely by governing the amount of oil in the unit.

A hydraulic coupling used in driving a blower is shown in Fig. 4.

In reduced speed operation the losses and instability characteristics of the hydraulic coupling are the same as for a magnetic coupling. The loss is caused by the torque being supplied to the constant speed member at one speed and taken from the variable speed member at a lower speed. With a constant torque load the loss is proportional to the reduction in speed.

The frictional losses of magnetic and hydraulic coupling will depend upon the type of construction and the number and type of bearings. Magnetic couplings have excitation losses, and hydraulic couplings require power for the oil pump motor.

The magnetic coupling has a very small air gap, so a pilot bearing is usually used to prevent misalignment of the two members. A pilot bearing is not necessary in ordinary hydraulic couplings because the clearances are usually relatively large. Pilot bearings are available for the larger hydraulic couplings and those units equipped with anti-friction bearings.

Variable speed couplings can be used wherever wound rotor motors are applicable, and the speed torque characteristics are very similar to those of the wound rotor motor. Both the hydraulic and the magnetic coupling are readily adaptable to automatic control, and a very little control power is needed. Hydraulic couplings give the stepless speed adjustment inherent with a control valve. Magnetic couplings may be equipped with rheostats having enough steps to give the number of speed points required.

Wound rotor induction motors

The wound rotor induction motor is possibly the simplest and the most common type of a-c variable speed drive. This type of motor is particularly applicable where speed adjustment is required for a load that

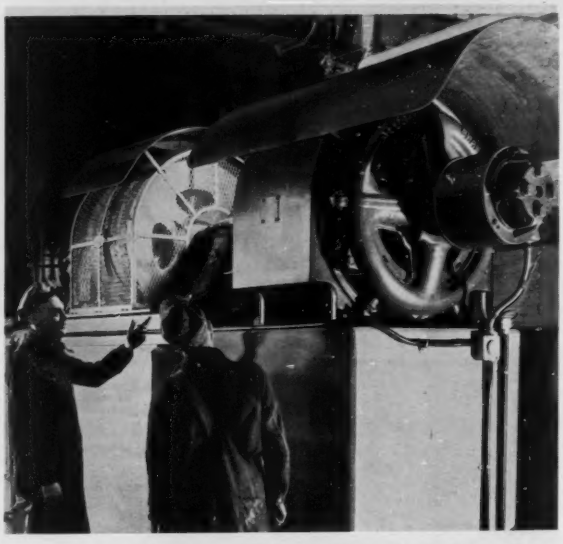


Fig. 3 — Variable speed magnetic coupling used in driving an induced draft fan with a 300 hp, 875 rpm squirrel-cage motor.

Fig. 4 — Variable speed hydraulic coupling used in driving a blower with a multi-speed, squirrel-cage motor.

also requires high starting torque, or the current inrush from the line on starting is to be limited.

By proper adjustment of the secondary resistance in the rotor circuit, the maximum torque of the motor may be had at starting without greatly exceeding an inrush current directly proportional to the percentage torque obtained. As the motor comes up to speed, if the secondary resistance is constantly reduced, the maximum torque of the motor can be maintained all the way up to full speed.

The secondary resistor can also regulate the running speed of the motor under load. On a constant torque load, the speed may be adjusted over a wide range very satisfactorily. However, on a varying torque load the speed regulation, especially at greatly reduced speeds, is very poor. Consequently, if a fluctuation in speed from changes in load is objectionable, the secondary resistor must be automatically adjusted or some other type of drive must be used. It is necessary to know the speed-torque characteristic of the load before designing a secondary resistor. Any variation from the values for which the control was designed will affect the speed control of the motor.

Speed reductions down to 50 percent of synchronous speed are common with almost any type of load. With a constant torque load even further reductions can satisfactorily be made, but with variable torque loads, such as fans and centrifugal pumps, the stability of the motor below half speed is poor.

The power absorbed in the secondary resistance is proportional to the reduction in speed at constant torque, and therefore the horsepower input to the stator will be approximately constant at all speeds.

Since at constant horsepower torque increases as speed decreases, and since current is proportional to torque, the output capacity of the motor will decrease with the reduction in speed. For that reason the wound rotor motor is unsuitable for drives where the horsepower requirement is independent of speed. For example, when a 100 hp 1200 rpm motor is running at 600 rpm, about 50 horsepower will be dissipated in the secondary resistance and about 50 horsepower will be available at the shaft. The motor is developing only 50 shaft horsepower, but 100 horsepower must cross the air gap and the power input to the motor will still be 100 horsepower, neglecting the variation in motor losses.

From this it is obvious that the efficiency of a

wound rotor motor is low at reduced speeds. Typical efficiency curves for wound rotor motors at various speeds are shown in Fig. 5. Curve "A" shows the trend of efficiency on a constant torque load such as a conveyor drive, and Curve "B" is typical of a variable torque drive such as a centrifugal pump or fan where the horsepower varies as the cube of the speed.

The efficiency of a motor at reduced speed on a variable torque drive is higher than that of the motor on a constant torque load. The reason for this is the way in which the secondary losses vary with load at various speeds (Fig. 6). With a constant torque load, the power absorbed by the secondary increases as the motor output decreases, while with the fan type load the secondary losses reach a maximum at about 30 percent load, which corresponds to about 66 percent speed.

The wound rotor motor has the mechanical advantage of being a self-contained unit and it usually requires less space than any other comparable a-c variable speed drive. The control, however, is much larger than that required for other a-c motors, but the secondary resistors, which are the bulk of the control, can be mounted away from the motor, so this disadvantage is not usually objectionable.

The most common type of control for smaller motors is the manually operated drum connected to grid resistors. The drum can be driven by a reversible motor to make remote operation simple. Drum controls are suitable only up to 500 horsepower, because of current limitations of the contacts. Control for motors above 500 horsepower are nearly always of the magnetic type and easily adaptable for remote or automatic operation.

Automatic liquid slip regulators are used for flywheel motor-generator sets and for constant torque loads in the larger ratings. Liquid regulators give stepless speed control and hence much better performance than a drum type rheostat which is limited to a definite number of control points.

Many wound rotor motors are used on variable torque loads, such as centrifugal fans and pumps, where the actual loss at reduced speed is relatively small. Constant torque loads which operate only a small part of the time at reduced speed also use wound rotor type motors to advantage.

Multi-speed squirrel-cage motors

Squirrel-cage motors with either one or two windings are available in practically all ratings. Each of the windings of a two-winding motor may be designed for two-speed operation, for example, 450/600/900/1200 rpm. This type of motor offers a choice of two, three, or four point speed control.

Multi-speed squirrel-cage motors are available for variable torque, constant torque, and constant horsepower loads. Multi-speed motors are convenient where closed speed control is not required. Some applications are:

1. Circulating water pumps and other pumps which may or may not be controlled by a discharge valve.
2. Constant torque loads where direct-current motors cannot be readily applied.
3. Fans and blowers with or without damper control. Curve 2 of Fig. 1 shows how a multi-speed cage motor is more efficient than a constant speed motor driving an induced or forced draft fan. This same curve would also apply to other types of variable torque loads, such as pumps where the output may be controlled by a valve.

Multi-speed wound rotor motors

The multi-speed wound rotor motor (Fig. 7) can be used whenever the required speed regulation is closer

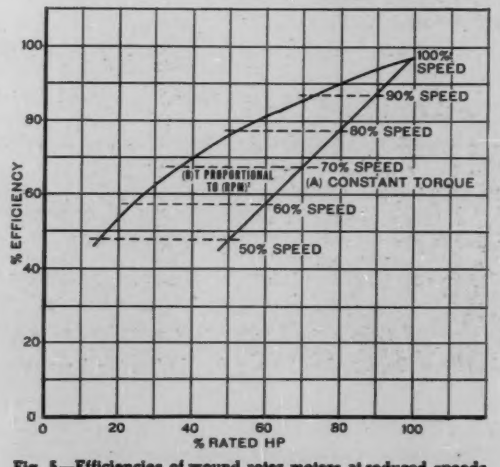


Fig. 5—Efficiencies of wound rotor motors at reduced speeds on constant and varying torque drives.

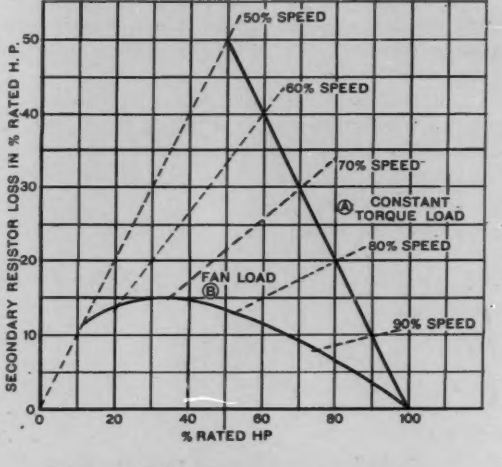


Fig. 6—Secondary losses at various speeds.

Fig. 7 — Two-speed, slip-ring induction motor, rated 150/75 hp, 1170/580 rpm, 440 volts.

than is possible with a multi-speed cage motor and where stable operation at large speed reductions is necessary.

The stator is wound like the stator of a multi-speed squirrel-cage motor; that is, if the speed ratio is two to one, a single winding is used, but if the speed ratio is other than two to one, two separate stator windings are required. When the speed ratio is two to one a single stator winding is used, but six slip rings are required on the rotor. If two stator windings are required for a speed ratio other than two to one, six rotor slip rings are still needed. Thus it is not practical to build wound rotor motors for more than two speeds because the number of slip rings would soon become cumbersome.

Except at lower operating speeds, this type of multi-speed motor offers a better speed characteristic than can be obtained with a single speed wound rotor motor because of the two base speeds.

An alternating current motor is inherently a constant speed device. The only reason that direct current motors exist today is because of their excellent adjustable speed characteristics. Any variable speed a-c drive must be a compromise, and certain good qualities inherent in an a-c motor must be sacrificed to obtain controlled speed. The main reasons for the popularity of squirrel-cage motors are the simplicity and economy of their construction. These features are cancelled when equipment is added to give variable speed.

However, in many cases it is more economical and practical to use an a-c motor with the necessary speed varying gear than to install an expensive direct current drive.

WHAT'S THE ANSWER?

Question— What are the objections to and what is the effect of a large single phase load on a three phase alternator? How may the results be calculated? — W. B.

Answer— Single phase or any unbalanced loads on three-phase alternators can be easiest analyzed with symmetrical components. This consists simply of resolving the unbalanced load into three balanced or "symmetrical" components, calculating the effect of each component separately, and then combining the results.

If the load is single-phase connected between two of the main terminals only (i.e., no current is drawn from either the third terminal or neutral), the positive and negative sequence components of the current will be each equal to 57.7 per cent of the single phase current. There will be no zero phase sequence component. The positive sequence component is exactly the same as the usual three phase balanced load current and produces no unusual results. The negative sequence component, however, induces currents in parts of the rotor, such as damper bars and metal pole collars, if any, and also in the field winding. This is because it produces a magnetomotive force which revolves at twice the normal frequency in relation to the rotor. Some parts of the rotor may overheat unless proper provision has been in the design. There should be either a low resistance damper winding or no damper winding at all.

The single phase performance is calculated by considering the effects of the positive and negative sequence components separately. The positive sequence component is simply balanced three phase current equal to 57.7 per cent of the single phase current as mentioned before and its effect is calculated in the usual manner. The negative sequence component requires additional internal voltage because of the negative sequence drop which is the product of the negative sequence current and the negative sequence impedance. The negative sequence impedance can be obtained by suitable tests.

Question— What is a "starting winding" on a direct-current generator? — F. W.

Answer— A starting winding consists of a few series turns on the shunt field poles, in addition to the compounding or stabilizing series winding. This starting winding is connected in series with the armature and across a suitable low-voltage battery for starting the diesel or gasoline engine driving the generator. This arrangement replaces the starting motor on the engine, or the starting air system on larger diesel engines.

"What's the Answer?" is conducted for the benefit of readers of ELECTRICAL REVIEW who have questions on central station, industrial or power plant equipment. Send all questions to the Editors of ELECTRICAL REVIEW.

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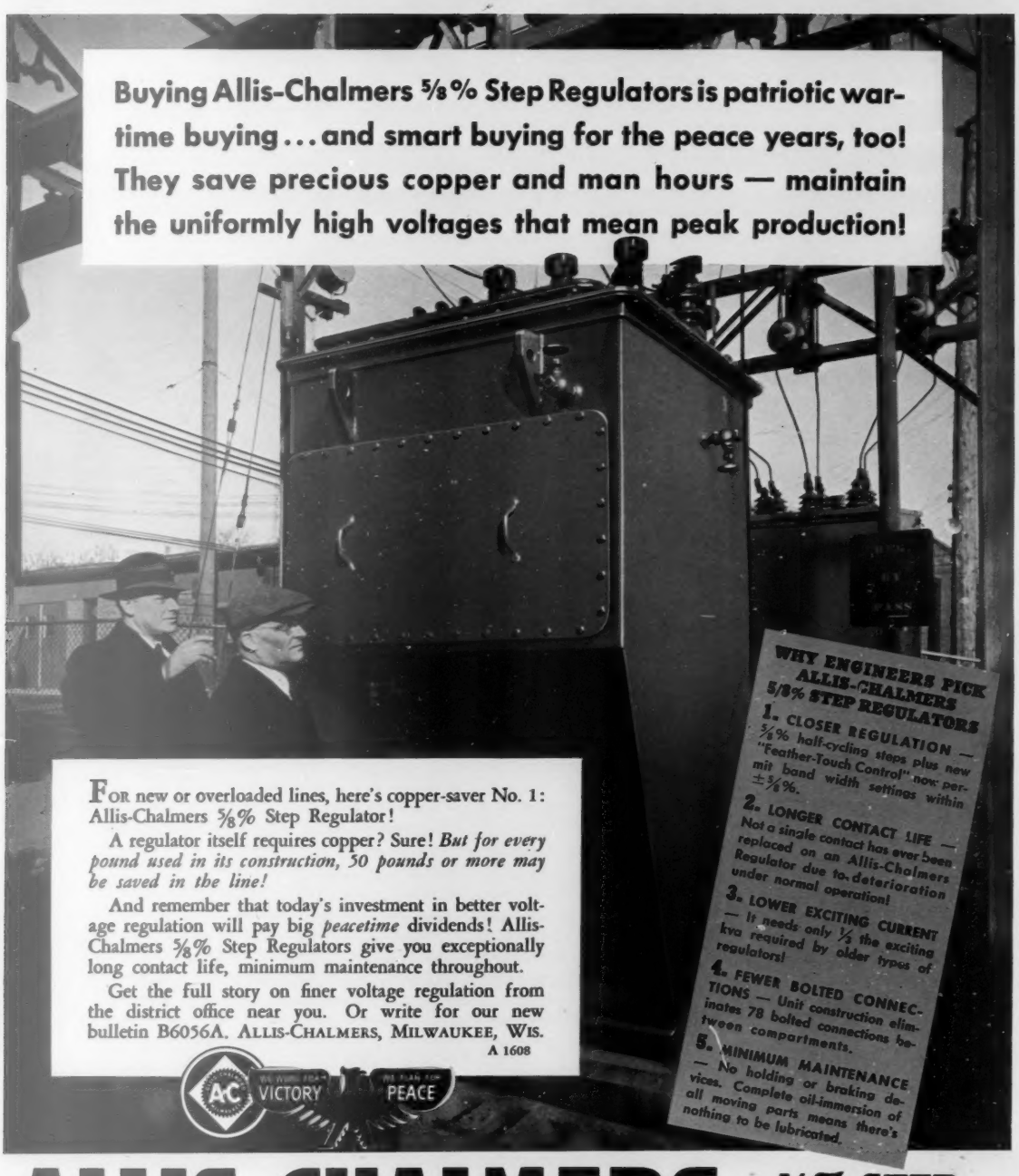

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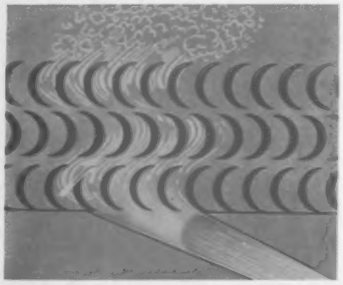

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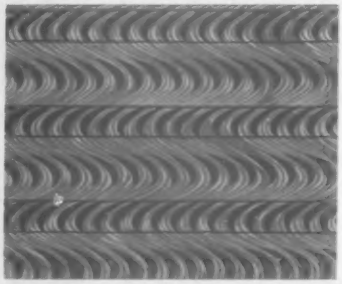

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